

ASPECTS OF THE COMPOSITION AND ORIGIN
OF ACHONDRITES AND MESOSIDERITES

by

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PREFACE

A BACKWARD GLANCE

The face of Science was altered by an event that took place on May 26th, 1751, but more than 40 years were to elapse before the change was recognized. On that day, a fireball exploded and split into two parts near the village of Hraschina in Croatia, in the northern part of what is now Yugoslavia. Two masses of iron, one weighing 40 kg, the other 9 kg, were observed to have fallen. The larger of these masses has been preserved to this day, and is known as the Hraschina meteorite (HEY, 1966).

The significance of this particular meteorite fall may not be immediately apparent, for meteoritic nickel-iron was known to early cultures in the Middle East prior to the discovery of smelting techniques, and was accordingly highly prized. Accounts of objects falling from the heavens occur in the literature of ancient China, Greece, and Rome, and in medieval writings. The concept of masses of iron and stone occasionally dropping from the sky appears to have enjoyed a reasonable degree of acceptance until about a century before the Hraschina fall. Then an attitude of scepticism arose among scientists. Their disbelief was fostered by the inconclusive nature of most of the reports of meteorite falls, by the supposed unreliability of eye-witnesses (mostly ignorant peasants), by the lack of preserved material to substantiate the reports, and by the general atmosphere of superstitious awe and religious mysticism that enshrouded most of the occurrences. The feeling that it was absurd to assign an extra-terrestrial origin to the metallic and stony materials that periodically rained on the Earth developed to the extent that many museums discarded collections of such objects as worthless reminders of a superstitious past. Hraschina, however, was spared this unfortunate fate. The evidence, in the form of the

and widely available when two events took place in 1969 that provided a great stimulus to the study of meteorites. The first occurred on 8th February, when the Allende carbonaceous chondrite shower fell in Mexico (CLARKE et al., 1970). The presence in these stones of inclusions of high-temperature minerals containing abundant refractory elements, particularly Ca, Al, and Ti, has afforded new insight into high-temperature condensation in the cooling solar nebula. However, an event of even greater importance and relevance to the present study took place on 20th July, 1969, when astronauts Neil Armstrong and Edwin Aldrin loaded 21.7 kg of samples from the Mare Tranquillitatis region of the Moon into their Landing Module and set out on the return journey to Earth. The samples from the Apollo 11 and subsequent lunar missions constitute the first extra-terrestrial material of known source and sampling environment available to scientists. Their study has benefited both meteoritics and terrestrial geological sciences, particularly with regard to processes of differentiation and the physical conditions of formation of fractionated mafic rocks at or near the surface of a planetary body. Much progress has been made in the last ten years in understanding the origin of the differentiated, more evolved types of meteorites, partly by the application of techniques used to study the lunar rocks, and partly by analogous reasoning from the results of lunar research.

It is into this framework that the present investigation falls. An attempt will be made in the following chapters to show how data were acquired on a selected group of meteorites - achondrites and mesosiderites - using the well-established techniques of mineralogy and petrology in conjunction with the newer methods of instrumental analysis, and how these data have been interpreted in the light of recent researches on meteorites and lunar rocks.

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Doctoral theses are meant to be solo efforts. The present work certainly fulfils this requirement, because all aspects of the investigation, from sample preparation through computing to draughting of the figures, were carried out by the writer virtually without assistance - a situation that makes it easy to assign responsibility for all errors, omissions, and deficiencies. Nevertheless, completion of a project of the size and scope of that reported here would have been impossible without the involvement, encouragement, and kind co-operation of many people. All of these people have my grateful thanks, but some must be singled out for special mention:

Prof. L.H. Ahrens initiated the project and maintained a close interest in it throughout its course. He also greatly increased the potential value and interest of the study by proposing the inclusion of compositional data on the mesosiderites. The Department of Geochemistry, through the good offices first of Prof. Ahrens and later Prof. A.J. Erlank, provided financial support in the form of bursaries for part of the period of the investigation and considerable financial assistance in the actual production of the thesis.

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ABSTRACT

This investigation had as its overall aims the collection and use of both new and existing information on achondritic and mesosideritic meteorites for three main purposes: (1) to establish the relationships between the three major achondrite classes - eucrites, howardites, and diogenites - and to assess the genetic significance of these relationships; (2) to determine whether the apparent similarity between the so-called basaltic achondrites (eucrites and howardites) and the silicate portions of mesosiderites is indicative of a genetic connection; and (3) to formulate, if possible, a model for the origin of the achondrites based on all available data. The starting point for the investigation was defined by a critical review and systematization of relevant information scattered throughout the literature up to the end of 1973.

The formation of the howardites, a range of polymict breccias with compositions that vary in a serial fashion between those of eucrites and diogenites, was investigated by a study of their petrography and by an extensive programme of electron microprobe analysis aimed at determining the extent of compositional variation present in their constituent mineral, lithic, and glassy phases. Four howardites chosen to represent the class - Bununu, Frankfort, Malvern, and Molteno - were so examined. A fifth meteorite, Binda, conventionally classed as a howardite (HEY, 1966) but later regarded as a cumulate eucrite (STOLPER, 1975a,b), was included for comparison with the howardites in the full realisation that its classification was problematical. Compositional data on 1,634 clasts in these five breccias were obtained from 2,938 microprobe analyses. The phases analyzed were pyroxene, plagioclase, olivine, silica minerals, chromite, ilmenite, metal, troilite, glass, and glassy microbreccia.

A comprehensive study of inter-element relationships, particularly of those involving refractory elements, was carried out to establish the relations between the three main achondrite classes and between the basaltic achondrites and the silicate fractions of mesosiderites for the purpose of gaining information on the possible modes of origin of these meteorites. Additional evidence on the genesis of the eucrites was obtained from mathematical modelling. These studies were based on the concentrations of major, minor, and trace elements in 42 bulk analyses of achondrites and mesosiderites. Most of the achondrites used were previously analyzed in this laboratory (McCARTHY, 1971; McCARTHY et al., 1972), but new analyses for 23 elements were performed by X-ray fluorescence spectrometry on five achondrite samples (Binda, Kapoeta, Molteno, and two samples of Malvern) and on the silicate fractions of seven mesosiderites (Emery, Estherville, Łowicz, Mincy, Mount Padbury, Patwar, and Vaca Muerta).

The accumulated petrographic and compositional data were used to evaluate existing hypotheses of achondrite formation. These were: (1) evolution of the achondrites from a common magmatic source by igneous differentiation, diogenites being the cumulates and eucrites the late-stage liquids produced by this process, which was followed by brecciation (e.g. DUKE and SILVER, 1967); (2) formation of the howardites by mixing, in varying proportions, of compositionally restricted diogenitic and eucritic materials and a minor chondritic component (JÉROME and GOLES, 1971); and (3) genesis of the eucrites by small degrees of low pressure partial fusion of a source region in the parent body, possibly followed by production of the more magnesian materials present in diogenites and howardites by further partial melting of the residues (STOLPER, 1977a). It was concluded that a two-component mixing model does not explain the observational data. The compositional bimodality of howarditic pyroxenes implicit in such a model is absent

of the mesosiderites by mixing of metal and howarditic or eucritic material. It was noted, however, that the higher content of FeO in howardites constitutes the main difference between them and the mesosideritic silicates. Recalculation of analyses after subtraction of 'excess' FeO, FeS, and P_2O_5 and Ni (assumed to be associated with the metal phase) resulted in coincidence of achondritic and mesosideritic trends in plots of major element relationships. This prompted the proposal that the source material of the achondrites - approximately represented by the average howardite - was formed from the most reduced, 'primitive' mesosiderites by oxidation of the high metal content of these mesosiderites, and that lesser degrees of oxidation produced mesosiderites with silicates compositionally intermediate to those of howardites and 'primitive' mesosiderites. These proposed relationships could be demonstrated, within reasonable limits of accuracy, for the major element concentrations of the 42 meteorites included in the study but not satisfactorily for the trace elements, possibly because of their redistribution during later, depth-related metamorphism of the 'primitive' mesosiderites.

It was deduced that the source material thus produced (from which the achondrites were derived) consisted of approximately 90% pyroxene (Wo_5En_{65}), 5% plagioclase (An_{94}), and 5% Cr-rich spinel; this is one of the alternatives proposed by STOLPER (1977a). The composition calculated from this mode plots on the olivine-pyroxene phase boundary of the silica-olivine-anorthite pseudo-ternary diagram (WALKER et al., 1972). The trend defined by the diogenites and howardites, whose more magnesian components are presumably attributable to the second stage of partial melting of the source region, also lies on this boundary. The close relationship between the calculated composition of the source material of the achondrites, which is similar to other estimates made (e.g. DREIBUS et al., 1977), and the observed trend of

the diogenites and howardites is of significance to the genetic model presented below.

Investigation of the petrography and phase chemistry of Binda showed that although some compositional variation - possibly attributable to minor fractionation - occurs in its constituent pyroxene and plagioclase and a small amount of glassy material is present, it is essentially a monomict breccia with a formational history different from the howardites that it resembles compositionally. It is a slowly-cooled cumulate that has been subjected to brecciation and cataclastic action in situ, without necessarily having been part of a regolith on its parent body. It was concluded from the study of inter-element relationships that it is neither a howardite nor a cumulate eucrite. Its constant association with mesosideritic silicates in plots of these relationships, together with its depletion in trace elements and metal, suggests that it is a silicate 'clot' from a fairly highly-oxidized mesosiderite.

The model proposed on the basis of the present investigation envisages formation of the achondrites in a parent body of asteroidal dimensions that accreted about 4.6×10^9 years ago from nebular material with abundances that were near-chondritic apart from depletion in volatiles. This body, for which 4 Vesta is a possible choice (CONSOLMAGNO and DRAKE, 1977), was heated by external sources and underwent primary differentiation during, or immediately following, accretion. Metal-silicate segregation was probably incomplete, and a pallasitic zone may have formed at depth in the body. It is proposed that at least the outermost parts of the body (subsequently to become outer mantle) were composed of material similar to the mesosiderites regarded as 'primitive'. Progressive oxidation of this material, possibly accompanied by segregation of metal, generated the pyroxene-rich rocks that were parental to the achondrites. Partial fusion of these source rocks

produced the 'primary' eucritic melts from which Fe-rich residual liquids and complementary cumulates were formed by fractional crystallization, this process continuing until plagioclase was exhausted from the source region. Eruption of the eucritic melts, possibly when a critical degree of partial melting had been attained, resulted in the formation of a crust in at least part of the parent body. The residues from this first stage of partial fusion constitute a series of pyroxenites ranging from the most Fe-rich diogenite hitherto reported (Yamato 75032) to the 'normal' diogenites.

If all plagioclase-bearing melts were removed from the source region(s), no further melting took place and only eucritic and diogenitic series were produced. If, however, some of the initial melts remained trapped in the residues, further addition of heat to the source region would have caused a second stage of partial fusion in which a range of pyroxene-plagioclase melts compositionally intermediate to the 'primary' eucrites and the new source material (residues + trapped feldspar-bearing liquids) was generated. These intermediate melts represent some of the components of howardites that were not contributed by eucrites or diogenites. Other such components - orthopyroxenes more magnesian than those of the diogenite series - were formed in the residues from the second stage of partial melting after exhaustion of trapped plagioclase-bearing melt.

The outermost parts of the parent body therefore presented, as a consequence of the interaction of processes of partial melting and crystallization differentiation, a wide compositional spectrum of materials for brecciation and mixing by impacting projectiles. In the regolith so formed, howardites and polymict eucrites were produced according to whether the material incorporated in them was biased towards the orthopyroxenitic residues or towards members of the eucrite series. Intrusive impact melts were formed locally and retained inclusions of the metal of the impacting bodies.

Lithification of the regolith and ejection of material from it produced the polymict achondritic breccias. Monomict breccias probably represent rocks that either were formed at depth in the crust of the parent body (e.g. residues and cumulates) or were protected by an overlying regolith deposit from all but the most violent impacts.

CHAPTER 1

INTRODUCTION

Beneath the stars, upon yon meteor

Ever hung my fate, 'mongst things corruptible.

Thomas Middleton (1570?-1627):

The Changeling, V, iii.

1.1 NATURE AND SCOPE OF THE PRESENT INVESTIGATION

Since its inception in 1961, the Department of Geochemistry in the University of Cape Town (U.C.T.) has been involved in meteorite research, and some of its earliest members were engaged in investigations on chondrites even prior to that date (e.g. AHRENS et al., 1960). Initial studies dealt with the inter-relationships and fractionation of lithophile elements in chondrites (e.g. AHRENS, 1964a, 1964b; VON MICHAELIS, 1969; VON MICHAELIS et al., 1969), but the scope of the investigation eventually widened to become a programme of research on stony meteorites in general. Important inter-element relationships first observed in chondrites, e.g. Ca/Al ratios (AHRENS et al., 1968), were found to hold good for basaltic achondrites also (AHRENS and VON MICHAELIS, 1969a), and other relationships were noted in the latter meteorite class, e.g. the inverse Mg/Ca relationship (AHRENS and VON MICHAELIS, 1969b). The focus of the investigation gradually moved to the achondrites and comparative studies of stony meteorites and lunar materials (AHRENS 1970a, 1970b, 1970c), and to consideration of the origin of the achondrites (McCARTHY et al., 1972, 1973).

The electron microprobe in the Department of Geochemistry was commissioned in 1973, and the meteorite research programme consequently entered a new phase. The dearth of data on the mineral chemistry of the

achondrites suggested a valuable contribution that could be made with the new equipment, and the likelihood that new data acquired in this way would shed additional light on the problems of the origin of the achondrites was appreciated. Accordingly, the present investigation was initiated. Its broad aims were two-fold: firstly, the study of a number of meteorites classified by HEY (1966) as howardites, a compositionally diverse class of achondrites intermediate between eucrites and diogenites, in order to collect basic data on these meteorites, some of which had never been studied in any detail; and, secondly, the interpretation of this new information in relation to specific hypotheses of howardite genesis. An additional objective was formulated during the course of the investigation: the general similarity between howardites and the silicate material of mesosiderites had long been recognized (PRIOR, 1918), and it was proposed to obtain data on the bulk chemical compositions of the silicate portions of mesosiderites for comparison with the howardites. The new data would allow assessment of the validity of the supposed genetic link between these two types of meteoritic material. These aims are formally presented in the following section of this chapter.

1.2 AIMS OF THE INVESTIGATION

The objectives of the present investigation may be set out as follows:

- (1) The compilation of a review of previous work relevant to the investigation.
- (2) Determination of the concentrations of major, minor, and trace elements present in five howardite samples (HEY, 1966) representative of the compositional range exhibited by this meteorite class, and in the silicate portions of seven mesosiderites.
- (3) The use of these bulk compositional data, in conjunction with selected

analytical data from the literature, to place constraints on the mode of origin and subsequent evolution of the three main classes of the achondrites in general, but with particular reference to the howardites.

- (4) The use of the data specified in (2) and (3) to effect comparisons between howardites and the silicate portions of mesosiderites, and thereby to test the validity of the hypothesis, presented by various research workers during the past 60 years (see Chap. 2), that these two types of meteoritic material have a common origin.
- (5) The detailed study of five howardites in order to obtain basic petrographic and compositional data on their constituents in sufficient quantity to enable meaningful statistical analysis to be carried out on these data, either in the present investigation or at a later date.
- (6) The use of the data specified in (5) to determine the chemical relationships present in the component phases of the individual howardites, and to compare these relationships in the howardites studied with other achondrites and lunar materials on which similar data have been published.
- (7) The testing, by means of the data obtained for the howardites and of the relationships observed within these data, of the validity of the two hypotheses that have been proposed for the origin of the howardites - derivation by fractional crystallization from a magma that was parental also to the eucrites and diogenites, followed by brecciation, or, alternatively, formation by physical mixing of diogenitic and eucritic material (see Chap.2).
- (8) The application of techniques of statistical analysis to the data obtained by the present investigation (and, where appropriate, to data from the literature) in order to substantiate the results of the testing described in (7). This part of the investigation was ultimately deferred to a later date.

- (9) The presentation of a model for the formation of the eucrites, howardites, and diogenites based on the results of the present investigation and on current hypotheses on the origin of these meteorites and the nature of their parent body (or bodies).
- (10) The presentation of any new evidence resulting from the investigation that has a bearing on the relationship between the main classes of achondrites and the silicate fraction of the mesosiderites, and therefore on the origin of the mesosiderites.

1.3 METEORITES INCLUDED IN THE INVESTIGATION

The bulk compositions of five howardite samples (Binda, Kapoeta, Malvern (UCT), Malvern (BLM), and Molteno) were determined by X-ray fluorescence spectrometry (XRF). The two samples of Malvern consisted of dust from sawing carried out at the University of Cape Town and at the National Museum, Bloemfontein. Their usefulness lay in the fact that large areas of the meteorite had been sampled by the sawing operations, thereby increasing the probability that the samples were representative of this extremely heterogeneous howardite. This factor was considered to outweigh the disadvantage of the slight contamination (e.g. by Cu) inevitably introduced by the diamond saws.

The mesosiderites whose silicate fractions were analyzed by XRF are Emery, Estherville, Łowicz, Mincy, Mount Padbury, Patwar, and Vaca Muerta. The analyses were carried out under the same conditions and, in several instances, at the same time as the analyses of the howardite samples.

The five howardites investigated by electron microprobe were Binda, Bununu, Frankfort, Malvern, and Molteno. It was originally intended to study Kapoeta also by this analytical technique, but this intention was shelved with the publication of the detailed investigation of that meteorite by DYMEK et al. (1976), which admirably supplemented the earlier work of

FREDRIKSSON and KEIL (1963).

Table 1.1 presents summarized information on the meteorite samples included in this investigation. It sets out the form in which the sample was obtained, the original mass from which material was selected for analysis, the techniques used to study the various meteorites, and the sources from which the samples were procured. The higher proportion of falls among the howardites studied than among the mesosiderites is a reflection of the general situation in these meteorite classes (HUTCHISON et al., 1977). A further mesosiderite find, Simondium, of which a sample had been obtained, was excluded from the investigation because it showed obvious effects of weathering.

1.4 MODE OF PRESENTATION OF THE DATA

Because of the wide scope and detailed nature of this investigation, the quantity of data obtained from it is considerable. Graphical presentation of results has been employed wherever possible, but the amount of basic data from which these results were derived renders conventional tabulation within the text of this report impracticable. The following modes of presentation have therefore been adopted for the various types of data resulting from this investigation:

- (1) Modal petrographic data are tabulated within the text.
- (2) Bulk chemical data, and all recalculations from these data, are tabulated conventionally at the appropriate places in the text.
- (3) All microprobe analyses and, in the case of minerals, the associated recalculations to atomic proportions, are listed on microfiche cards appended to this report as follows:

Appendix 1 - A directory of sample names generally accompanied by a very brief description of the material analyzed

Appendix 2 - The microprobe analyses in their original form

Table 1.1. Summary of meteorites investigated, techniques used, and form, mass, and sources of the samples

Meteorite	Study method			Form of sample(s)	Mass ⁺ of sample(s):g	Source of sample	Original sample number
	Pet.	XRF	EMP				
H BINDA	1	X	1	F, T	11.4	Australian Museum, Sydney	DR8281
O BUNUNU*	1	-	1	T	-	Smithsonian Institution	NMNH1571
A FRANKFORT*	1	-	1	T	-	Smithsonian Institution	NMNH --
R KAPOETA*	-	X	-	F	9.55	British Museum (Nat. History)	BM1946, 141
I MALVERN (UCT)	* 6	X	4	S } F, T S }	2.67	National Museum, Bloemfontein	K1600
T MALVERN (BLM)					2.62		
E S MOLTEÑO*	4	X	4	F	62.0	Mrs M.C. Trembath, Berkshire	---
M EMERY	-	X	-	F	20.02	U.S. National Museum	USNM5604
S ESTHERVILLE*	-	X	-	P	3.36	U.S. National Museum	USNM1722
O ŁOWICZ*	-	X	-	F	11.80	Warsaw University	32
I MINCY	-	X	-	F	10.0	Arizona State University	207a
E MT PADBURY	-	X	-	P	8.0	U.S. National Museum	USNM3454
R PATWAR*	-	X	-	F	6.0	Arizona State University	634.1
T VACA MUERTA	-	X	-	F	12.15	S.A. Museum, Cape Town	36

Notes: Meteorite classification according to HEY (1966) and HUTCHISON et al. (1977); * = Fall;

+ = Total mass of sample available for study. Abbreviations: Pet. = petrographic (number of sections studied is specified), EMP = electron microprobe (number of sections studied is specified), XRF = X-ray fluorescence spectrometry, F = fragment(s), S = sawings, P = powder, T = polished thin section

Table 1.2. Distribution of mineral and lithic phases analyzed by electron microprobe in the five achondrites studied

METEORITE	M I N E R A L S						L I T H I C C L A S T S				
	Chromite	Ilmenite	Metal	Olivine	Plagio- clase	Pyroxene	Silica Minerals	Troilite	Glass	Glassy Micro- breccia	Devit- rified Glass
Binda	55/34	5/4	1/1	n.f.	105/48	132/59	5/2	n.a.	n.f.	28/9	0
Bununu	23/18	32/17	12/9	n.f.	101/62	202/105	n.f.	n.a.	23/11	36/11	0
Frankfort	23/11	n.a.	n.a.	n.f.	81/49	176/107	1/1	n.a.	n.f.	3/1	0
Malvern	24/17	90/50	129/69	7/6	209 [*] /143	393/242	1/1	22/11	104/58	159/69	23/14
Molteno	60/33	46/35	72/41	15/9	127/83	237/111	n.f.	24/19	71/37	81/27	0
Totals	185/113	173/106	214/120	22/15	623/385	1140/624	7/4	46/30	198/106	307/117	23/14

Notes: The figure preceding the oblique denotes the number of analyses performed, that following it the number of analyzed mineral grains or lithic clasts.

n.a. - not analyzed n.f. - not found * includes 42 partial analyses
 0 - not distinguished from other glassy material

Appendix 3 - The averaged compositions of the material analyzed, calculated from the data contained in Appendix 2 after exclusion of determinations that are demonstrably inaccurate

- (4) All CIPW norms computed from the bulk chemical analyses of the howardites and silicate fractions of the mesosiderites investigated, and from the microprobe analyses of glassy and devitrified materials present in the howardites, are listed on microfiche cards as Appendix 4 and Appendix 5 respectively.
- (5) Representative examples totalling 10% of the data listed in Appendix 3 are tabulated at appropriate places throughout the text in order to illustrate the arguments contained therein without the necessity of reference to the microfiche card. All norms appropriate to analyses that appear in the text are tabulated in the text in a format abbreviated from that of the appendices.

Appendix 2 contains 2,938 analyses, while Appendix 3 contains 1,634 averaged analyses computed from them. Stated differently, 2,938 electron microprobe analyses were carried out on a total of 1,634 mineral and lithic phases in howardite breccias during the course of the present investigation. The distribution of these analyzed phases among the five howardites studied is summarized in Table 1.2.

The extensive use of graphical presentation in this work necessitated standardization of the abbreviations used for the names of meteorites that appear in the figures. These abbreviations are set out in Table 1.3. In a few figures, additional meteorites have been included; the abbreviations that identify them are explained in the appropriate figure captions. Likewise, the symbols used to represent the achondrites and mesosiderites included in the investigation in the plotting of bulk chemical relationships are presented in Table 1.4.

Table 1.3. Abbreviations used for analyzed meteorites plotted in figures throughout this work

<u>Eucrites</u>		<u>Howardites contd</u>	
Allan Hills 7605	AH	Malvern (McCarthy)	MCC
Béréba	BE	Malvern (UCT)	MU
Cachari	CA	Malvern (von Michaelis)	MV
Haraiya	H	Molteno	MT
Juvinas	J	Yamato 7308	Y7
Lakangaon	LK	Zmenj	Z
Macibini	MA	<u>Diogenites</u>	
Moama	MO	Ellemeet	EL
Moore County	MC	Johnstown	JT
Nuevo Laredo	NL	Shalka	SH
Pasamonte	PS	Tatahouine	T
Serra de Magé	SDM	Yamato 6902	Y6
Sioux County	SC	<u>Mesosiderites</u>	
Stannern	ST	Barea	BA
<u>Howardites</u>		Dyarrl Island	DI
Binda (McCarthy)	BM	Emery	E
Binda (Simpson)	BS	Estherville	ES
Bununu	BU	Łowicz	Ł
Chaves	CH	Mincy	MY
Frankfort (F)	FF	Mount Padbury	MP
Frankfort (T)	FT	Patwar	P
Kapoeta	K	Vaca Muerta	VM
Malvern (BLM)	MB		

Table 1.4. Key to the symbols used to represent the various classes of meteorites in figures relating to bulk chemical relationships in this work. Binda and Macibini have special symbols because their classification is discussed in detail in the text.

Eucrites	▲
Howardites	△
Diogenites	◆
Mesosiderites	▼
Binda	●
Macibini	○

CHAPTER 2

A REVIEW OF PREVIOUS WORK

Thus men catch knowledge by throwing
their wit into the posteriors of a
book, as boys do sparrows with fling-
ing salt on their tails.

Jonathan Swift (1667-1745):

A Tale of a Tub

2.1 INTRODUCTION

Previous work on the classes of meteorites studied in the present investigation is extensive but scattered. Some of it is reported only in the form of abstracts and unpublished theses. This chapter presents a comprehensive review of previous investigations that include data on the compositions, ages, and possible origins of the eucrites, howardites, diogenites, and mesosiderites. It was undertaken in order to define the state of knowledge at the start of the present study. The time range covered is from the early years of this century up to and including 1973, when the analytical phase of the current investigation began. The material reviewed was drawn from a number of sources, one of which was a bibliography of the literature on achondritic and stony-iron meteorites (REID et al., 1977) in the compilation of which I collaborated. Results of research relevant to the present study published after 1973 are discussed in the appropriate places throughout the text of this report.

2.2 EARLY STUDIES

The difficulty and expense of obtaining chemical analyses largely

restricted early research on meteorites to the recording of observational data on the circumstances attending the fall or discovery of particular meteorites, and to petrographic observations, both macroscopic and microscopic. This early work, as in most branches of Science, was directed towards description and classification, and culminated in a workable classification based on mineralogical composition (PRIOR, 1920) that is still in use in a modified form (MASON, 1962a). The amended version was followed in the present investigation.

Apart from the work of PRIOR (1918, 1920) on the mesosiderites, the early researches included no systematic studies on the classes of meteorites dealt with in this investigation, nor on the inter-relationships of these classes, but individual members of the classes were described in some detail, e.g. the mesosiderites Simondium (PRIOR, 1910, 1918, 1921) and Estherville (MERRILL, 1920), the diogenites Tatahouine (LACROIX, 1932) and Johnstown (HOVEY, 1925), and the eucrites Béréba and Juvinas (LACROIX, 1926), Pasamonte (FOSHAG, 1938), and Moore County (HESS and HENDERSON, 1949). The more significant investigations generally did include chemical analyses, and compilations of these were made by FARRINGTON (1911), MERRILL (1925) and UREY and CRAIG (1953). The last of these may be regarded as marking an approximate divide between the older and newer techniques of chemical analysis and, as shown by FAIRBAIRN et al. (1951), care must be taken in the use of the older chemical data.

2.3 THE PERIOD 1949-1962

The state of knowledge on meteorites and their origin at the end of the earlier, 'descriptive' phase of meteorite research may be gauged from a review in DALY (1943). The beginnings of a more modern phase, characterized by a more analytical, more interpretive approach to the data may be seen in papers such as that by HESS and HENDERSON (1949). This study provided

analyses of the eucrite Moore County and of its constituent minerals, recognized its cumulate character, and concluded, from a detailed study of pyroxene exsolution, that the meteorite had been formed at about 1135°C by crystal settling in a basaltic body in the deeper part of the crust of a parent planet. A further conclusion, based on the absence of inversion of its pyroxenes and tridymite, was that the meteorite had been suddenly ejected from the parent body, possibly during catastrophic disintegration. Another advance relevant to the present investigation was made by WAHL (1952), who applied the terms 'monomict' and 'polymict', borrowed from sedimentology, to brecciated meteorites, and recognized that eucrites and diogenites are monomict, whereas howardites are polymict. From his own observations and the literature, he reviewed the occurrence of 'foreign' fragments in chondrites and achondrites and noted the presence of fragments of eucrite in all the howardites studied. Two of these howardites - Le Teilleul and Luotolax - contain also small pieces of diogenite, and Luotolax incorporates some fragments of glass and what is probably devitrified glass. Wahl recognized that only unbrecciated achondrites and monomict achondritic breccias could have formed by direct magmatic crystallization and concluded, from the intermingling of achondritic and chondritic materials, that all stony meteorites originated from a single parent body, possibly of asteroidal character.

Whether or not all the conclusions reached by these two papers are correct is of lesser importance than the change in approach and treatment that they typify. Unfortunately, the example they set was not immediately followed by other writers. For about a decade afterwards, much of the published work on the achondrites dealt with esoteric topics - the analysis of rare elements and gases, isotope studies, rare minerals, and age determinations - while the mesosiderites were completely neglected. Many of these studies were little more than analytical exercises, albeit for the development of necessary techniques, and offered no interpretation of the signifi-

cance of the data they provided in terms of the origin and evolution of the meteorites investigated. The development of chemical and physical techniques had temporarily outstripped their application, and many of the basic data needed for interpretation of the new information these techniques provided were still lacking. In radiometric dating, however, an important fact emerged: the eucrite Nuevo Laredo was found, by the $^{207}\text{Pb}/^{206}\text{Pb}$ method, to have an age of 4.55×10^9 years, apparently identical to those of the Earth and chondrites (PATTERSON, 1955, 1956).

The period under consideration produced a fair amount of speculation on the ultimate origins of meteorites. UREY and CRAIG (1953) regarded meteorites as having been derived from asteroidal bodies accreted at low temperatures and subsequently heated and differentiated to produce the achondrites in their outermost zones. Bombardment by smaller bodies generated a rubbly (brecciated) surface layer on these asteroids, and a collision between two of the larger members caused the formation of the two most common types of chondrites, plus the iron meteorites and the achondrites. LOVERING (1959) deduced, from the remanent magnetization and the presence of tridymite in the eucrite Moore County, that it had formed at a depth of 10-40 km in the outer mantle of its parent body, and that it had cooled to 560°C (c.f. HESS and HENDERSON, 1949) while in a magnetic field, implying the existence of a metal core in the body. GOLES et al. (1960) calculated that meteorite parent bodies had a maximum radius of about 250 km, and suggested that achondrites were formed in a hotter environment than chondrites. These concepts were further developed by FISH et al. (1960), who showed that segregation of metal and silicate phases and mineral differentiation could take place in small bodies within a reasonable time span, and postulated that meteorites originated from a single body of asteroidal dimensions heated by radioactive sources that are now extinct. In this body, achondritic meteorites such as howardites formed in deeper, hotter regions than did chondrites. Carbona-

aceous chondrites occupied the cold surface layer, and mixing of the various materials was brought about by volcanic activity. MASON (1960) proposed that chondrites were produced by the recrystallization of carbonaceous chondrite material, and that some of the chondrites aggregated into a body (or bodies) that differentiated to give the achondrites. RINGWOOD (1961) discussed a model for the evolution of a typical parent body accreted from cold dust of solar composition. Internal heating of this body, which was compositionally similar to carbonaceous chondrites, producing melting, convection, and volcanism, with segregation of a metallic phase and differentiation of the chondritic material. These processes resulted in a metal core, a zone of mixed iron and silicates, a chondritic mantle, and an achondritic crustal zone. Subsequent collisional disruption of such a body (or bodies) ultimately produced the asteroids and the meteorites.

Application of the Rb-Sr dating technique to meteorites (GAST, 1962) showed that a period of chemical differentiation took place in the parent body 4.3 to 4.7×10^9 years ago.

2.4 THE PERIOD 1962-1966

The 'revolution' that overtook the earth sciences in the 1960's affected the science of meteoritics also. New trends in the study of meteorites started to appear in the literature about 1962, having their origins in factors discussed in the Preface to this work. To set the scene for the rapid developments that followed came the necessary systematization of the state of knowledge then current. This was performed by MASON (1962a). One of the most valuable contributions made by Mason's book was the modification of PRIOR's (1920) scheme of classification. The literature prior to 1962 contains many examples of confused and inconsistent classification that obviously hampered understanding of the problems investigated. It was fairly common, for instance, to draw no distinction between eucrites and howardites.

The importance of this simplified classification to later work cannot be over-estimated, although it may eventually be superseded by a scheme more firmly linked to the origins of the various types of meteorites.

In MASON (1962a), a fractional crystallization model for the origin of the achondrites that was based on phase relations in the system anorthite-forsterite-silica (ANDERSEN, 1915) was presented. The model set constraints on the composition of an initial silicate melt from which a series of rocks having the same sequential chemical and mineralogical characteristics as the diogenites, howardites, and eucrites could have crystallized. Only compositions in that part of the olivine field of the system that lies between the MgSiO_3 -anorthite join and the olivine-pyroxene cotectic could have produced the olivine-deficient pyroxene, and pyroxene-plagioclase, aggregates that constitute these achondrite classes (MASON, 1962a, p. 116). The model was able also to account for the observed compositional progression from hypersthene to Fe-rich pigeonite in these achondrites, and could be related to the ideas of RINGWOOD (1961) on the origin of pallasites. The origin of the mesosiderites was treated only insofar as to repeat the suggestion of PRIOR (1918) that they had been formed from the invasion of a eucritic magma by another of pallasitic composition, and to draw attention to the conclusion of LOVERING (1962) that their origin was more complex than supposed by Prior. For instance, according to Lovering, the Dyarri Island mesosiderite appears to have originated from the intrusion of solid basaltic achondrite material by a metal magma. Lovering also reviewed the three theories of meteorite evolution then current without coming to a firm conclusion whether parent bodies were of lunar or asteroidal dimensions. He did conclude, however, that meteorites evolved either in a single body or in a number of similar bodies, not, as suggested by UREY (1959), in two different kinds of body ('primary' and 'secondary' objects) of which the larger, 'primary' type disintegrated to provide the achondritic and iron meteorites

and the debris that ultimately aggregated to form the smaller, 'secondary' chondritic parents.

The beginnings of more interpretive work on the achondrites may be seen in MOORE (1962), whose study of their petrochemistry paved the way for later work in the Department of Geochemistry at U.C.T. However, as Moore himself realised, this attempt to establish chemical relationships in the achondrites was only partly successful because of the limitations of the chemical data (from UREY and CRAIG, 1953) and the unsatisfactory classification of a number of meteorites studied. Nevertheless, variation diagrams used in the study clearly showed the serial chemical relationship, and possible fractionation trend, in diogenites, howardites, and eucrites, the distinction between diogenites and enstatite achondrites, and the inverse Mg/Ca relationship in the main achondrite classes. The mineralogy of meteorites also received attention at this time; systematic reviews were produced by MASON (1962b) and RAMDOHR (1963). The first major study of the mineral chemistry of an achondrite dealt with the howardite Kapoeta (FREDRIKSSON and KEIL, 1963). These authors investigated the concept (somewhat archaic in terms of modern ideas on impact and brecciation processes) of 'light-dark' structure in stony meteorites in an attempt to explain in mineralogical terms the presence of primordial noble gases in only the dark portions of gas-rich meteorites. They found that both lithologies are composed of the same minerals with the same compositions, but that the constituents of the dark portions are much finer-grained. Selective trapping of the gases in shock-disordered minerals in the fine parts was suggested as a possible mechanism that agreed with their conclusion that 'light-dark' structures originated through shock. The observation that Kapoeta is "a volcanic-tuffaceous agglomerate of minerals from different sources, formed under varying conditions" and the range of pyroxene compositions reported (about En_{85} - En_{30}) are both of particular interest to the present investigation. Surprisingly, in

view of these observations, Fredriksson and Keil concluded that Kapoeta is not a polymict breccia.

Other contributions to the understanding of the achondrites at this time were the review of the hypersthene achondrites by MASON (1963) and a study of Stannern by VON ENGELHARDT (1963), but the most important advance was a systematic investigation of the petrology of the basaltic achondrites (DUKE, 1963), later published in an extended form that included data on mesosiderites and electron microprobe analyses of pyroxenes in Nuevo Laredo, Sioux County, Juvinas, and Petersburg (DUKE and SILVER, 1967). The unpublished thesis includes the most comprehensive and thorough petrographic study of the basaltic achondrites carried out to date. Duke realised that the basic data essential for the interpretation of more advanced work, e.g. trace element investigations, were lacking. He concluded that the mineralogical, textural, and chemical evidence all point to a common magmatic origin for the basaltic achondrites, although a variety of cooling environments is represented in the meteorites and their constituent fragments. The trends observed suggest differentiation in a Skaergaard-like body, but from a starting material compositionally different from that for terrestrial rocks and under conditions of low partial pressures of oxygen. Duke recognized that the heterogeneity of the howardites precludes the possibility of their representing quenched liquids, and suggested that these breccias formed in accumulations of impact-produced ejecta on the surface of the parent body. The Moon was thought to be the parent body. In the later work (DUKE and SILVER, 1967), it was proposed that howardites originated in the lunar highlands while the mare areas were covered by eucritic material, though an asteroidal origin was not ruled out.

In an important paper on the origin of gas-rich meteorites, SUESS et al. (1964) showed that the incorporation of primordial rare gases in Kapoeta could not be attributed to shock, as proposed by FREDRIKSSON and

KEIL (1963), but was best explained by exposure of the meteorites, after complicated formational processes, to particle radiation such as the solar wind. The other effects of shock observed by Fredriksson and Keil were not questioned. However, Suess et al. considered Kapoeta a true polymict breccia, not a product of in situ brecciation as proposed by Fredriksson and Keil.

The metal phase of achondrites and mesosiderites received some attention at this time. LOVERING (1964) suggested that the metal in the eucrite Macibini and the howardite Binda formed by partial reduction of a basic magma parental to the achondrites. However, DUKE (1965) regarded the metal in many basaltic achondrites as a direct product of magmatic crystallization, though in others it may have formed by post-crystallization reduction of pyroxene. He also attributed the fact that eucrites have lower Ni contents than howardites to removal of Ni during derivation of the eucrites from howarditic material by magmatic differentiation or partial melting (DUKE, 1963). An analysis of the metal in the Estherville mesosiderite was included in REED (1964), and the scarce opaque minerals in Binda were described by RAMDOHR (1966).

An important contribution was made by TAYLOR et al. (1965), who, on the basis of oxygen isotope analyses of minerals in stony meteorites, divided these meteorites into three groups, one of which was made up of the meteorite classes concerned in the present investigation - diogenites, basaltic achondrites, and mesosiderites. The other two groups were composed essentially of chondrites and carbonaceous chondrites respectively. Taylor and his co-workers suggested that the meteorites within each group are genetically related; those with which the present study deals exhibit the same oxygen isotopic characteristics as a comparable sequence of magmatically differentiated rocks from the Skaergaard intrusion. However, the $^{18}\text{O}/^{16}\text{O}$ ratios of these meteorites are significantly different from those of chondrites (and terrestrial rocks), suggesting that the achondrites and mesosiderites were

not derived from chondritic source material by fractional crystallization. The authors concluded also that the three groups defined by differing oxygen isotope ratios are probably genetically unrelated to one another, and may have originated in different regions of the solar system. They state categorically that the two groups comprising the most important achondrites and the majority of the chondrites "could not have been in exchange equilibrium with a common oxygen reservoir during their formation".

PINSON et al. (1965) reviewed and extended the work on the Rb-Sr chronology of stony meteorites, and concluded that chondrites and achondrites differentiated from a source material of uniform $^{87}\text{Sr}/^{86}\text{Sr}$ at the same time, viz. 4.55×10^9 years ago if the decay constant of ^{87}Rb is taken as 1.38×10^{-11} per year. This figure is in exact agreement with the lead age obtained by PATTERSON (1956). From that time onwards, the meteorites studied by Pinson et al. appear to have remained closed systems, not subject to further heating or igneous activity in their parent bodies.

2.5 THE PERIOD 1966-1969

Further petrographic and compositional data on several of the meteorites included in the present investigation appeared in print at this time. MASON and WIIK (1966a, 1966b) described the howardites Kapoeta and Frankfort, with bulk chemical analyses, and drew attention to the close relationship of Frankfort to the diogenites and the possibility of a common origin for howardites and diogenites. MÜLLER and ZÄHRINGER (1966) found fairly large differences between the light and dark portions of Kapoeta, contrary to the results of FREDRIKSSON and KEIL (1963). Mg and C occur in higher concentrations in the dark (matrix) material, while the reverse is true for Al, Ca, and K. Müller and Zähringer sought to explain these chemical differences as arising from the addition of carbonaceous chondritic material to the dark portions, but MASON and WIIK (1966a) interpreted them

to indicate that the dark, fine-grained material contains more pyroxene and less plagioclase than the lighter parts of the meteorite. A detailed description of the Mount Padbury mesosiderite was supplied by McCALL (1966), who characterized the silicate inclusions present as olivine achondrite, eucrite, and diogenite. He postulated that the achondritic material had crystallized slowly in the deeper parts of the mantle of a small planetary body, and had been brecciated prior to successive invasions by immiscible melts, first of nickel-iron, and later of troilite. Compositional data on the matrix material and some of the enclaves in this unusual meteorite were also reported. The Bununu howardite was the subject of a paper by MASON (1967) that includes a bulk chemical analysis and a review of the pyroxene-plagioclase achondrites, in which the author defended their subdivision into eucrites and howardites and condemned the term 'basaltic achondrites' as misleading. Mason suggested further that the pallasites should be included as the initial step in the differentiation sequence from a chondritic parent material through Ca-poor to Ca-rich achondrites, and warned that the classification of meteorites into four groups (irons, stony-irons, chondrites, and achondrites) might well be obscuring genetic relationships. A further paper by the same author (MASON, 1968) reviewed the compositions of meteoritic pyroxenes and noted the narrow compositional range in diogenites, in marked contrast to the wide range present in howardites, eucrites, and mesosiderites, even within a single member of these classes.

The question of the origin of gas-rich meteorites was again considered by MAZOR and ANDERS (1967) in a study of the Jodzie howardite. Their results supported the contention of MÜLLER and ZÄHRINGER (1966) that the dark portions of such meteorites contain an admixture of carbonaceous chondrite material that is absent from the light portions, thereby accounting for the chemical differences and the differences in rare gases between the light and dark parts. They suggested that the carbonaceous component, whose presence

in the dark material was confirmed by enhanced concentrations of Kr, Xe, C, Ni, Br, and Bi, consists of interplanetary dust bombarded by the solar wind prior to accretion on the surface of a meteorite parent body and subsequent incorporation into impact breccias. However, they conceded that the major element variation between the light and dark material in gas-rich meteorites could be ascribed to differences in the pyroxene/plagioclase ratio, as suggested by MASON and WILK (1966a).

The first determination of rare-earth element abundances in a howardite (Bununu) was reported by PHILPOTTS et al. (1967), who examined the constraints imposed by their data on the differentiation processes that may have operated during the formation of the calcium-rich achondrites. These considerations pointed to a type of differentiation involving addition or subtraction of a solid phase, most probably hypersthene, with very low concentrations of the rare-earths and other trace elements that have been shown as a group to be unfractionated relative to chondrites (SCHMITT et al., 1963, 1964b). Proposing an alternative that took the extensive brecciation of the achondrites into account, the authors made the interesting observation that a mechanical mixture of eucritic and diogenitic material would also satisfy the data.

Some of the problems of obtaining reliable radiation and gas retention ages for the Ca-rich achondrites became evident in the work of HEYMANN et al. (1968, 1969) and GANAPATHY and ANDERS (1969). These include the almost complete loss of ³He by diffusion from feldspar (for which a correction procedure was developed in the 1968 paper), the difficulty of obtaining samples representative in terms of the proportion of feldspar present, the uncertainty whether some of the samples investigated are eucrites or howardites, and - incredibly - the lack of basic data on concentrations of K, U, and Th! However, from the review and the original work of these authors there emerged several salient points: the K-Ar ages of the eucrites fall in the range

$2.4-4.4 \times 10^9$ years; the U-He ages are all systematically shorter, giving rise to the idea that the parent body underwent collisional heating late in its history; and, in contrast to the howardites, several of which are gas-rich, none of the eucrites contain light primordial gases. This last observation caused GANAPATHY and ANDERS (1969) to modify the conclusion reached by HEYMANN et al. (1968), that eucrites and howardites formed in close proximity to one another, to that of regarding the howardites as having originated in a stratigraphically higher position, near the surface of the parent body, favourable for the implantation of solar-type gases. HEYMANN et al. (1968, 1969) were unable, from the evidence gained by their investigations, to decide whether Ca-rich achondrites are of lunar or asteroidal origin, but were of the opinion that the slow cooling rate of the mesosiderites, reputed to contain eucritic inclusions, and the existence of unbrecciated eucrites, favoured their common formation in a body of asteroidal dimensions.

PAPANASTASSIOU and WASSERBURG (1969), in reporting the results of an investigation of the isotopic composition of Sr at the time of formation of planetary objects, stated (p. 369) that "any precise interpretation of the K-Ar ages would appear to be very uncertain". The refinements they introduced into the technique of Rb-Sr dating enabled them to define the age of a number of eucrites as $4.39 \pm 0.26 \times 10^9$ years, and to show that these meteorites formed within a period of at most four million years, irrespective of whether they differentiated from material of solar photosphere or chondritic Rb/Sr abundances. MARSHALL (1968) reported a Pb-Pb age of 4.94×10^9 years for the mesosiderite Bondoc, but some uncertainty appears to attach to this determination because of an unexplained excess of ^{207}Pb .

Other studies relevant to the present investigation made in the period under review include that on the black glass in the Cachari eucrite by FREDRIKSSON and KRAUT (1967), who established its chemical identity with the bulk composition of the meteorite and proposed an origin from pre-atmospheric

hypervelocity impact. Further use was made of the electron microprobe to study the compositions of phases present in achondrites and mesosiderites (REID and LOVERING, 1969). These authors made the interesting observation that "a single eucrite breccia may contain fragments of similar composition, with wide variations in texture, or may embrace virtually the entire range of phase compositions observed within the group", which may imply that not all the eucrites are truly monomict. DEUSER (1968) studied Fe-Mg-Al relationships in the achondrites, using mainly the data of UREY and CRAIG (1953), and showed that the main achondrite classes could be clearly distinguished on a ternary plot of these elements. However, the work suffers from the quality of the data used and some minor deficiencies in the meteorite classification of MASON (1962a). WIIK (1969) published an important compilation of meteorite analyses, and DUKE (1969) reiterated the hypothesis of a lunar origin for basaltic achondrites using as supporting evidence the similarity between eucrites and the mare soils analyzed by Surveyor 5 and 6, and between the howardite compositional range and the highlands material on which Surveyor 7 supplied data. The enrichment in refractory elements in the sequence chondrites-howardites-eucrites, and the close coherence between Ca and various other refractories, were noted by AHRENS and VON MICHAELIS (1969a) in an extension of their previous studies on chondrites to the basaltic achondrites. The Ca/Al relationship received particular attention. The authors observed that this ratio is either unfractionated, or only slightly fractionated, throughout the sequence of meteorites studied, and concluded that relationships such as this point to physical processes having played a dominant role in the formation of these meteorites. On the basis mainly of the Ca/Al relationship, Ahrens and von Michaelis disagreed with the conclusion of DUKE and SILVER (1967) that the chondrites and basaltic achondrites are not directly related.

The chemical characteristics of the basaltic achondrites were further studied by AHRENS and VON MICHAELIS (1969b), who drew attention to

the uniformity of Si and Fe and to the inverse Mg/Ca relationship in howardites and eucrites, and noted that fractionation of the Na/K ratio between chondrites and basaltic achondrites is only slight. They suggested, even more strongly than in the earlier paper, that physical processes in the primitive parent material and not magmatic differentiation determined the composition of the basaltic achondrites. This view was not shared by SCHNETZLER and PHILPOTTS (1969). Their investigation of Ba and rare earth element concentrations in Ca-rich achondrites led them to regard the brecciated achondrites as mixtures of 'liquids' that had suffered no significant losses or gains of either pigeonite or plagioclase through fractionation. They postulated fractionation of hypersthene as the mechanism responsible for the sequence of uniform enrichment in rare earths present in the Ca-rich achondrites, because that mineral is not an important carrier of these elements (c.f. PHILPOTTS et al., 1967). The data indicated also that the unbrecciated eucrites Serra de Magé and Moore County are cumulates from a melt of 'normal' eucritic composition, that diogenites are orthopyroxene cumulates from similar eucritic liquids, and that the shocked achondrite Shergotty may not be closely related to the other pyroxene-plagioclase achondrites.

Progress in the understanding of the mesosiderites at this time included an account of the mineralogical character and chemical composition of Patwar (JAROSEWICH and MASON, 1969), in which the view was expressed that mesosiderites are mixtures of nickel-iron and howarditic silicates, with some troilite. A major advance, however, came from the work of POWELL (1969a, 1969b, 1971), which constitutes the first systematic study of this group of meteorites since that of PRIOR (1918). The mesosiderites were divided into three sub-groups on the basis of textural criteria that indicate increasing degrees of recrystallization and re-equilibration of the heterogeneous components. Microprobe analyses of the minerals present revealed great compositional variability, that in the pyroxenes resembling the range found in

basaltic achondrites by DUKE and SILVER (1967). These analyses established also that the olivines of mesosiderites are compositionally distinct from those of the other major group of stony-irons, the pallasites. The investigation included bulk analyses of the metal and silicate fractions of nine mesosiderites, and a comparison between these silicate analyses and the compositional ranges encountered in howardites and eucrites. From this comparison, Powell concluded that there is "a general similarity" between the silicate portions of mesosiderites and the Ca-rich achondrites, but that in many respects the mesosiderites constitute a group distinct from all other meteorite groups. Following FUCHS (1969), he suggested that the major discrepancy between the compositions of howardites and the silicate fractions of mesosiderites - the high concentration of P in the latter - could be accounted for by oxidation of that element, much of which was originally present in solution in the metal. The textural and compositional features of the metal (POWELL, 1969b) were interpreted as having resulted from either initially rapid cooling that decreased to the exceptionally slow rate of $0.1^{\circ}\text{C}/10^6$ years in the $500\text{-}350^{\circ}\text{C}$ range, or rapid cooling followed by re-heating to 500°C and subsequent very slow cooling. Powell considered the low cooling rate more likely to be achieved in a parent body of lunar, rather than asteroidal, dimensions. The low content of Ni in mesosideritic metal was regarded by Powell as precluding an origin for the mesosiderites involving the invasion of basaltic achondrite silicates by a melt of pallasitic composition (PRIOR, 1918; LOVERING, 1962). Moreover, he concluded that the metal phase was solid at the time of mixing with the silicate material. Because of the complex cooling history revealed by his investigation, the evolutionary model proposed by Powell for the mesosiderites involves "magmatic differentiation, followed by brecciation, metal-silicate mixing, insulation by burial, metamorphism, and, ultimately, removal from the parent body".

2.6 THE YEARS 1970 AND 1971

At about the same time as the publication of Powell's results, data were presented that appear to refute conclusively the lunar origin suggested for basaltic achondrites (DUKE and SILVER, 1967; DUKE, 1969) and mesosiderites (POWELL, 1971). TAYLOR and EPSTEIN (1970) showed that the lunar rocks and minerals returned by the Apollo 11 mission are significantly richer in ^{18}O than basaltic achondrites, diogenites, mesosiderites, and other stony-iron meteorites. This conclusion did not invalidate arguments in favour of the parent body (or bodies) of these meteorites having lunar dimensions, but did point to an origin in a different part of the solar system from the Earth, the Moon, and the chondrites, all of which have basically similar $^{18}\text{O}/^{16}\text{O}$ ratios.

Also at this time, the concept of a mixing origin for the howardites, touched on briefly in previous publications, was formally presented by JÉROME (1970) and JÉROME and GOLES (1971). These authors rejected previous suggestions that howardites may have originated through fractional crystallization of a melt of chondritic composition (MASON, 1962), or that eucrites were produced by partial melting of howardites (DUKE, 1965; PHILPOTTS et al., 1967). They proposed instead that howardites are mechanical mixtures of two discrete meteorite types - eucrites and diogenites - that may possibly have been co-magmatic. However, their attempts to derive howardite compositions by simple linear mixing procedures carried out on averaged elemental abundances in eucrites and diogenites met with only partial success, and they postulated the addition of a chondritic component to the mixture to offset the systematic excesses of certain elements (e.g. Ni, Co, P, Cu, and possibly Na and Fe) above the values calculated. As evidence in support of this, they cited the presence of carbonaceous chondrite material in gas-rich meteorites (MÜLLER and ZÄHRINGER, 1966; MAZOR and ANDERS, 1967) and the deduced presence of about 1.9% of similar material in the lunar soil (GANAPATHY et al., 1970). Jérôme and Goles further concluded that the absence of a chondritic component

in the eucrites studied implied a more complex brecciation history for howardites, possibly in a parent body regolith. They observed also that the eucrites themselves constitute a differentiation series, and speculated that their conclusions on howardites should apply equally to the stony portions of mesosiderites. They made the suggestion that the main classes of achondrites, some mesosiderites, and possibly the chassignites may all have originated in a single location, e.g. within a layered complex in a parent body.

The Cape Town group's investigation of the composition of the stony meteorites continued with a study of refractory elements in basaltic achondrites and in Apollo 11 and Apollo 12 rocks and soil (AHRENS, 1970a). These elements occur in higher concentrations in eucrites than in howardites, but the reverse is true for Mg and Cr. Ahrens noted the sympathetic relationship between Mg and Cr in basaltic achondrites, in the average Apollo 11 soil, and in lunar rock 12038. He observed also a positive correlation between Ba and the REE (exemplified by Nd) in chondrites, basaltic achondrites, and Apollo 12 rocks and soils. AHRENS and DANCHIN (1970) had commented that the eucrite Stannern is the basaltic achondrite most closely resembling the lunar rocks because of its high content of refractory elements, and this similarity is borne out by the Ba/Nd plot also. AHRENS (1970a) suggested that such compositional similarities may have arisen from similar conditions of formation early in the history of the solar system.

AHRENS (1970b) showed that enrichment in refractory elements relative to other basaltic achondrites is present also in the eucrite Nuevo Laredo, and that the degree of enrichment varies from about 5-10% for Sc and Sr to as much as 80% for Ba, Ti, Zr, and the REE. This variability was examined in more detail by the same writer (AHRENS, 1970c), who presented a refractory enrichment sequence from chondrites through basaltic achondrites to the Apollo 11 fines. Ahrens also pointed out that the Ca/Al weight ratio characteristic both of the chondrites and of the main achondrite classes

(1.08) is far greater than the maximum observed in calcic plagioclase, which is the major Ca- and Al-bearing phase in these meteorites. The constancy of the Ca/Al ratio is therefore difficult to explain in terms of the behaviour of plagioclase alone. A further contribution from the Cape Town group at this time took the form of a comprehensive review of published chemical data on the basaltic achondrites (AHRENS and DANCHIN, 1971).

MASON and MELSON (1970) reported on a comparative study of the Apollo 11 crystalline rocks and microbreccias and the basaltic achondrites, exemplified by Moore County and Kapoeta. They found that, because of their high content of Ti and K, the Apollo 11 basalts do not match eucritic compositions. However, the lunar microbreccias were observed to bear a close similarity to Kapoeta, except for the absence of glass spherules and the lack of evidence for a high degree of shock (e.g. plagioclase transformed to maskelynite) in the howardite. Mason and Melson concluded that howardites, like lunar breccias, originated from the lithification by meteorite impact of part of a regolith-like deposit, but suggested that the absence of extreme shock effects may indicate that the meteorite parent body was smaller than the Moon.

Other investigations carried out at this time include that of WASSON and BAEDECKER (1970) who deduced, from comparative studies of Ca, Ge, In, Ir, and Au, that the basaltic achondrites did not originate at the Apollo 11 site. EHMANN and REBAGAY (1970) showed that Ca-rich achondrites are greatly enriched in Zr and Hf relative to chondrites, and that Ca-poor achondrites are correspondingly depleted in these elements. They ascribed this effect to processes of fractional crystallization, by analogy with terrestrial examples. They also noted, in passing, the unusually low content of Zr in Binda. TERA et al. (1970) presented arguments essentially similar to those of GAST (1965) against the Earth, the Moon, and the basaltic achondrites having been differentiated from material with chondritic abundances. Their

conclusion that the parent materials for all of these bodies must have been highly depleted in K, Rb, and Cs and enriched in Ca, Sr, Ba, U, and Th relative to carbonaceous chondrites implies widespread chemical fractionation of primordial material throughout the early solar system if the basaltic achondrites originated in a different region from the Earth and Moon.

Preliminary results obtained from a new technique were reported by McCORD et al. (1970). Using spectral reflectivity, these workers compared the surface characteristics of several of the larger asteroids with meteorite samples. Their observations indicated that the surface of Vesta is similar in composition to certain basaltic achondrites (Nuevo Laredo was used for the comparison), and that an exact match of characteristics would be obtained from a meteorite that contained slightly more magnesian pyroxene. The reflectance data from Vesta showed little resemblance to the spectra of samples from the other meteorite classes, or to the spectral characteristics of Apollo 11 samples. These observations constitute the first direct indication of the identity of a possible meteorite parent body.

Two howardites that figure prominently in the present investigation were the subject of publications in 1971. Malvern, previously analyzed by VON MICHAELIS (1969) and classified as a howardite (VON MICHAELIS et al., 1969), was described as resembling a lunar breccia by JÉROME (1971) mainly because it contains glassy materials. This preliminary observation was followed by a mineralogical description of some of the lithic and glassy fragments in the meteorite (JÉROME and CHRISTOPHE MICHEL-LÉVY, 1971). These authors suggested that Malvern had been formed in a manner analogous to the lunar breccias, because it bears a closer resemblance to impact, rather than volcanic, breccias, although some of its constituents appear to have had a volcanic origin. The first petrographic and chemical data on Molteno were presented by FROST (1971), who classified the meteorite as a howardite. Fine-grained dark material present was considered to have been produced by

extreme shock, and was compared to pseudotachylite. The range of pyroxene compositions in Molteno was reported as similar to that determined for Kapoeta by FREDRIKSSON and KEIL (1963). A new analysis of the diogenite Johnstown, together with a compilation of chemical data on the meteorite taken from the literature, was published by MASON and JAROSEWICH (1971). BUNCH and KEIL (1971) presented the results of an investigation of meteoritic chromite and ilmenite that included microprobe analyses of these minerals in eucrites and mesosiderites.

The Ca/Al ratio in mesosiderite silicates was examined by McCARTHY and AHRENS (1971), who concluded that the value for these meteorites (0.88) is distinctly lower than that determined for chondrites and basaltic achondrites (1.08). They regarded this observation, which was based on analyses in the literature, as proof that mesosiderites are not mixtures of metal and howarditic silicates. The origin and possible cosmological significance of this particular inter-element relationship were discussed by WILLIS et al. (1971). These authors interpreted the lunar fines as "fairly well mixed averages" of the major element compositions of the rocks of the Moon's surface, and noted that the Ca/Al ratios of these fines are similar to the value for the stony meteorites. They suggested that such observations of the uniformity of the Ca/Al ratio point to the relative proportions of Ca and Al having been established in 'closed-system' condensation from the solar nebula. Consequently, the mineralogical composition of extra-terrestrial materials is an expression of this and other refractory inter-element relationships, rather than the reverse. The close relationship between Sr and Eu was cited as a further example of this suggested principle in operation in lunar rocks and stony meteorites.

A study of fossil particle tracks in Kapoeta (WILKENING et al., 1971) led to the conclusion that the light solar-type gases in gas-rich meteorites were not introduced by a carrier such as cosmic dust, but by

particle irradiation during brecciation and mixing of the components of these meteorites. WILKENING (1971) suggested that the heavier, planetary-type rare gases were introduced by a carrier material, this process of implantation taking place at the same time as the other. Wilkening and her co-workers noted, in the course of their investigation, that the minerals that make up the Kapoeta howardite are not a compositionally random aggregate. Instead, they show related compositions that are suggestive of a differentiation sequence. In particular, the Kapoeta pyroxenes 'mimic' the compositional range of the pyroxenes determined for the diogenite-howardite-eucrite sequence by REID and LOVERING (1969).

Compilations of data on meteorites are few and far between. A valuable addition to their number was made by MASON (1971). The reference work that resulted from his organizational efforts contains reviews of element abundances in meteorites, each contributed by a specialist in a particular element or group of elements.

2.7 1972

The genesis of howardites by the mixing mechanism proposed by JÉROME and GOLES (1971) was further studied by McCARTHY et al. (1972), using data first presented by McCARTHY (1971). McCarthy and his colleagues pointed out that although the Ca/Mg relationship in howardites could have been established by the orthopyroxene fractionation required for formation of howarditic compositions by igneous differentiation of a mafic silicate melt, the constancy of the Ca/Al ratio necessitated the maintenance of the same relative proportions of plagioclase and clinopyroxene during crystallization over the whole range of orthopyroxene fractionation. In their view, this requirement constituted a severe constraint on this mode of howardite genesis. They cited also the different trends of enrichment of certain of the refractory elements present in howardites and eucrites as evidence

against the differentiation model, arguing that these different trends could not have been produced by the observed variations in pyroxene composition in the two meteorite classes. McCarthy and his collaborators considered that a process of physical mixing - essentially a dilution of eucritic material by variable amounts of orthopyroxene, in the form of diogenite - accounted better for the inter-element relationships present in the basaltic achondrites. They noted also that, since both diogenites and eucrites contain pyroxenes with limited compositional ranges, howardites formed by the mixing, in varying proportions, of these two meteorite types ought to have bimodal populations of pyroxenes, and suggested that this important constraint on the mixing hypothesis should be tested by detailed electron microprobe measurements. This suggestion provided the initial stimulus for the present study.

Other relevant investigations carried out at this time include that on the howardite Washougal (JÉROME and CHRISTOPHE MICHEL-LÉVY, 1972). An account was given of the mineralogical and chemical composition of the meteorite, and of the types of lithic fragments present. Among these is a large clast of monomineralic olivine rock that the authors acknowledge to be difficult to account for on the basis of the mixing hypothesis of JÉROME and GOLES (1971). Moreover, as in the earlier paper, the presence of a chondritic component had to be invoked to explain elemental discrepancies arising from the mixing of the compositions (the eucrite Juvinas and the diogenite Shalka) proposed for the generation of Washougal.

Few investigations have been carried out on the diogenites as a class, but one such study is that of GOOLEY (1972). It included microprobe analyses of the phases present in nine diogenites, but, unfortunately, no bulk chemical analyses of these meteorites. Gooley concluded that all diogenites are products of igneous fractionation and that they all had similar, but not necessarily identical, cooling histories and formational environments. He envisaged their formation in a layered ultramafic complex, analogous to the

Stillwater intrusion, and explained the textural and compositional variations observed within the meteorite class as arising from the crystallization of individual diogenites in different layers of the complex.

SCHMITT et al. (1972) presented data on the abundances of Na, Al, Sc, Cr, Mn, Fe, Co, and Cu in 17 achondrites as part of an analytical programme directed at obtaining high quality chemical data on a wide range of stony and stony-iron meteorites. Their results support a close relationship between howardites and eucrites but suggest that these achondrites are not directly related to any of the chondrites by igneous fractionation. HUTCHISON (1972) advanced arguments in favour of basaltic achondrites and diogenites having condensed from the solar nebula prior to chondrites. Part of the achondritic material vaporized during a hiatus in the condensation process, and refractory residues from this partial evaporation aggregated with newly condensed material to form the chondrites. TAKEDA and REID (1972) observed that the pyroxenes in basaltic achondrites appear to have cooled more slowly than the pigeonites in lunar mare basalts, and that these meteoritic pyroxenes resemble the Fe-rich pigeonites of non-mare rocks. The mesosiderite Estherville was analyzed completely for the first time by NELEN and MASON (1972), who pointed out that the polymict nature of this meteorite breccia probably accounts for the differences between their analysis of the silicate material and the partial analyses carried out by JÉROME (1970) and POWELL (1971). Lastly, MASON (1972a) produced an updated review of the mineralogy of meteorites, incorporating new data on the compositional ranges of pyroxene, plagioclase, and olivine.

2.8 1973

The problem of achondrite genesis was again considered by McCARTHY et al. (1973), who dissociated themselves from suggestions that eucrites originated on the Moon, citing as their reason the outcome of the oxygen isotope

studies of TAYLOR and EPSTEIN (1970). These isotope data did, however, indicate that diogenites and eucrites originated in the same part of the solar system (TAYLOR et al., 1965). McCarthy and his colleagues proposed an igneous fractionation model based on the observed abundance trends of refractory and alkali elements in eucrites. They considered the existence of cumulate eucrites (Moore County, Serra de Magé) as proof that partial melting alone could not have generated the eucrites, and used the refractory and alkali elements to show that liquids with compositions comparable to known eucrites could have been produced by simultaneous fractionation of pyroxene and plagioclase, in relatively constant proportions, throughout the compositional range of the non-cumulate eucrites. The calculated ratio of pyroxene to plagioclase (53:47) in this fractionation scheme is similar to the mineral proportions observed in Moore County and Serra de Magé, which were regarded as the fractional cumulate material. The authors of this work considered that the parental liquid from which the eucrites were formed was derived from a liquid similar to, or possibly more mafic than, the monomict howardite Binda by subtraction of about 54% of material with the composition of average diogenite. The suggestion was offered that the ultimate source of the parental eucritic liquid may have been compositionally similar to the C4 carbonaceous chondrites, which have suitably low abundances of K.

Other workers expressed different views on the formation of the achondrites. FISHER (1973) investigated the U content of achondrites and concluded that his data, used in conjunction with data on Al and K, did not support the hypothesis of derivation of the basaltic achondrites by simple fractional melting of chondritic material. The U and Th determinations of MORGAN and LOVERING (1973) led them to the conclusion that the mixing model of JÉROME and GOLES (1971) was a more feasible mode of origin for howardites than derivation from a melt of the composition of H-group chondrites as proposed by MASON (1967). Morgan and Lovering did, however, admit the

possibility that diogenites might have been formed from a reduced chondritic melt, but a further fractionation process would have been required for the attainment of the observed abundances of U and Th.

Some attention was given to the mineral constituents of achondrites at this time. Data on the opaque minerals of achondrites feature in a comprehensive treatment of the stony meteorites (RAMDOHR, 1973), and the results of a microprobe investigation of achondritic olivines were summarized by DESNOYERS and JÉROME (1973). These authors observed that the olivine in howardites occurs only as isolated grains (c.f. JÉROME and CHRISTOPHE MICHEL-LÉVY, 1972). The compositional range present in the eight howardites studied was determined as 11 to 83 mole % fayalite, and wide ranges were noted in individual meteorites. The olivines from Malvern and Macibini proved to be the most Fe-rich reported from achondrites up to that time. Desnoyers and Jérôme could suggest no likely source for the rare olivines in howardites, and concluded: "In order to account for the composition of the howardites it appears more and more that several minor additional components are required to improve the first-approximation eucrite-diogenite mixing model."

One such minor component in Kapoeta was identified as dark fragments of carbonaceous chondrite, probably C2 or C3, by WILKENING (1973), who cautioned against regarding all the material of dark appearance in that meteorite as chondritic in composition. She suggested that some of the dark constituents may be similar to the incompletely devitrified material reported from the Washougal howardite by JÉROME (1970). Comparison with lunar studies indicated that impact velocities of infalling interplanetary matter were lower in the source location of Kapoeta than on the Moon, as shown by the survival of the carbonaceous chondrite fragments in an unshocked condition in the meteorite breccia. Wilkening concluded that howardites are low-grade microbreccias, comparable to the class 0 or class 1 lunar breccias (WILLIAMS, 1972), derived from a thoroughly reworked parent body regolith.

Independent evidence for the origin of gas-rich meteorites in regolith deposits came from a study of micrometeorite craters on the surfaces of spherical glassy grains in Kapoeta (BROWNLEE and RAJAN, 1973). These proved morphologically similar to craters described from glass spheres in lunar soils (e.g. HARTUNG et al., 1972) and, together with the presence of track-rich grains and a rare gas component, pointed to the formation of Kapoeta from impact-produced material resident in a regolith. The compositional uniformity of the glassy spheres studied suggested that the surface of the parent body was chemically more homogeneous than the lunar surface, and that the parent body was probably much smaller than the Moon.

Further refinement of the Rb-Sr age determination technique enabled ALLÈGRE et al. (1973) to assign an age of $4.59 \pm 0.04 \times 10^9$ years to the eucrite Juvinas. This result further demonstrated the very early date at which igneous activity took place in a meteorite parent body. Moreover, the authors deduced from their data that the parent body was of at least lunar dimensions. TATSUMOTO et al. (1973) used new values for the isotopic composition of primordial Pb and for the decay constants of ^{235}U and ^{238}U to study small time differences in the formation of certain meteorites. Their work showed that Sioux County and Nuevo Laredo were formed $4.528 \pm 0.010 \times 10^9$ years ago, and that the Angra dos Reis achondrite is about 27×10^6 years older than these eucrites. This result is in agreement with the conclusion reached by PAPANASTASSIOU and WASSERBURG (1969), using Rb-Sr dating methods.

During the period under review, the mesosiderites received attention from several workers. MASON and JAROSEWICH (1973) commented on the incompleteness or inadequacy of many of the available analytical data on mesosiderites, and on the difficulties inherent in the reliable sampling and analysis of these meteorites. They sought to improve the situation by analyzing three mesosiderites that had not previously been studied - Barea, Dyarri Island, and Emery. Microprobe analysis showed a wide range of

pyroxene compositions to be present in each of these meteorites; some variation occurs also in the calcic plagioclase, the other major silicate phase present, and in the minor olivine (JAROSEWICH and MASON, 1969; POWELL, 1971). A rough inverse correlation between the amount of metal present and the Fe content of the pyroxenes was noted in the mesosiderites as a class, but no correlation between the Ni concentrations in the metal and the FeO/MgO ratio in the silicates was evident in the published analyses reviewed by Mason and Jarosewich. The reviewers therefore concluded that Prior's Rules, empirically formulated to explain such relationships in the chondrites (PRIOR, 1920), do not apply to mesosiderites. They also examined critically the conclusion of McCARTHY and AHRENS (1971) that the Ca/Al ratio in the silicates of mesosiderites is significantly lower than in the stony meteorites. While noting that the published data appear to support this conclusion, they observed that there is considerable variation in the ratio, and maintained the view first stated by PRIOR (1918), that the silicates of howardites and mesosiderites are essentially similar. They recognized the high content of P in mesosiderite silicates as an important difference from howardites, but considered that the new data presented in their paper confirmed the conclusion of FUCHS (1969), that the phosphates in mesosiderites originated from reaction between the silicates and P in solid solution in the metal. Mason and Jarosewich concluded that a common origin for all mesosiderites is possible, and suggested derivation from a slightly oversaturated magma that initially crystallized Mg-rich pyroxenes and tridymite such as are present in the anomalous stony-iron meteorite Steinbach. The explanation offered by these authors for the present form of the mesosiderites is the disruption of a single asteroid in which gravitational segregation of silicate and metal phases was in an incipient stage. This hypothesis accounts for the compositional uniformity of the metal and the absence of severe shock effects in the silicates.

Of the two other papers dealing with mesosiderites that were published at this time, the first (JAIN and LIPSCHUTZ, 1973) confirmed that virtually none of the mesosiderites whose classification is well established has undergone a high degree of shock. This observation militates against a lunar origin for these meteorites, as advocated by POWELL (1971), because escape velocities could not have been attained without producing recognizable shock effects in the kamacite phase. The other investigation (BILD et al., 1973) concluded that mesosiderites are surface breccias formed on an asteroidal parent body, and that the metal phase accreted after the formation of the silicates.

2.9 SUMMARY OF THE STATE OF KNOWLEDGE AT THE START OF THE PRESENT INVESTIGATION

As noted earlier, the object of the literature survey reported in this chapter was the definition of the state of knowledge on the main classes of achondrites and on the mesosiderites at the start of the present investigation, thereby establishing the starting point for the project. In the sections that follow, an attempt is made to summarize that starting position in the topics that are most important to an understanding of the origins and inter-relationships of these meteorites.

2.9.1 Structural, mineralogical, and chemical relationships

The distinctions between diogenites, howardites, and eucrites had been clarified, and the brecciated character of almost all of these meteorites had been recognized, as had the fact that polymict meteorite breccias could not possibly have been formed by direct crystallization from a melt. The serial nature of the chemical relationships existing between diogenites, howardites, and eucrites had been established from the study of element pairs such as Ca/Al and Ca/Mg. The restricted ranges present in the bulk composi-

tions of diogenites and eucrites had been contrasted with the compositional variability of howardites. These characteristics had been noted also in the compositions of pyroxenes in the members of these meteorite classes; Kapoeta, Petersburg, and Molteno among the howardites were known to contain pyroxenes with a wide range of compositions, whereas diogenites and eucrites studied did not show this feature. Similar variability had been established for the olivines in howardites, but not for the plagioclases. Mesosiderites also had been shown to contain a variety of pyroxenes, an observation seemingly in accordance with the long-held idea that they had been formed by mixing of howarditic silicates and metal. Comparison of the pyroxenes of basaltic achondrites and mare basalts had indicated that the meteoritic types had cooled more slowly.

Studies of inter-element relationships in the main chondrite and achondrite classes, and in lunar rocks, had indicated a progressive but unequal enrichment in refractory elements in that sequence. Of particular interest was the Ca/Al ratio, which had been shown to be unfractionated in the chondrites and achondrites. Its constancy in the apparent differentiation series from diogenites to eucrites could not be accounted for by fractionation of plagioclase alone.

Attention had been paid to some unusual features of howardites. Glassy materials had been observed in Malvern and had led to a comparison with lunar breccias; similar dark glass of impact origin in the eucrite Cachari had been found to be identical in composition to the bulk meteorite, but this had not been demonstrated for Malvern. The light and dark lithologies in Kapoeta had been shown to be essentially of the same composition, but in this and other gas-rich meteorites the presence of very minor amounts of carbonaceous chondrite material that had acted as carrier for planetary-type gases had been proved. Some small dark fragments in Kapoeta had been identified as C2 or C3 carbonaceous chondrites.

2.9.2 Formational processes

In the earlier part of the period reviewed, it was thought that meteorites were formed by the following processes: cold accretion from the solar nebula of material similar to carbonaceous chondrites was followed by a heating episode that effected segregation - complete or partial - of metal from silicates; differentiation of these silicates produced a chondritic mantle and an achondritic crust in the body; collisions with similar bodies, and subsequent disruption, generated the main varieties of meteorites - irons, stony-irons, chondrites, and achondrites - each of which had formed separate zones in these bodies. Later, however, doubt was cast on the origin of achondrites by differentiation or partial melting of chondritic material. Such an origin was incompatible with new data on trace elements, particularly U and Th, and with oxygen isotope data that suggested that chondrites and achondrites were formed in different parts of the solar system. Debate on whether the meteorite parent bodies were of lunar or asteroidal dimensions continued, with the latter gaining favour as it had been shown that processes of segregation and differentiation could operate in bodies of small size.

With the chondrites having been shown to be unlikely source materials from which the main classes of achondrites could have been fractionated, some confusion is apparent in the literature over the details of a scheme of igneous differentiation for the genesis of the achondrites. There appears to be general agreement that a sequence of rocks with compositions similar to the howardites and eucrites could have been produced by fractionation of hypersthene, which accumulated to form the diogenites. This model is apparently consistent with most of the observed trace element concentrations, but does not explain the constant Ca/Al ratio in the basaltic achondrites nor the different enrichment trends shown by the refractory elements. These considerations, together with the evidence supplied by brecciation and shock effects in the meteorites, prompted the proposal of an alternative model for

the formation of howardites near the end of the period under review. This hypothesis postulated that howardites are mechanical mixtures of eucrites and diogenites in varying proportions, but was not specific on the origin of the end-members. A fairly large amount of chondritic material was required in the mixture to obtain the minor and trace element abundances observed in howardites, and it was also recognized that other source rocks, e.g. olivine-bearing varieties, had contributed to the mixture. For the eucrites and diogenites, formation in a layered igneous complex was favoured, but there was little clarity on the source liquid from which the various compositions were derived. One view was that diogenites are cumulates from a eucritic liquid, while another maintained that eucrites are differentiates obtained from a parental composition approximately that of Binda less 54% average diogenite; pyroxene and plagioclase fractionation in the proportions observed in the cumulate eucrites was claimed to be capable of bringing about the required differentiation. Metal in the achondrites was considered to have been produced by reduction in some cases, but to be primary in others.

Similarity of the oxygen isotope ratios of basaltic achondrites, diogenites and mesosiderites pointed to a genetic relationship between these meteorite classes, possibly within a single layered planetary body. The silicates of howardites and mesosiderites were thought to be essentially similar, and the major difference - the high concentration of P in mesosiderites - was ascribed to reaction between metal and silicates. It had been suggested that the mesosiderites were formed by invasion of basaltic achondrites by a pallasitic or metal magma, but pallasitic mixing had not met with universal acceptance although there appears to have been agreement that the metal was introduced after the formation and brecciation of the silicates. Furthermore, the supposed identity of the silicates in howardites and mesosiderites had been challenged on the basis of differences between the Ca/Al ratios of the two meteorite classes.

2.9.3 Parent bodies

The idea of a single parent body for all meteorites had originated from the observed mixing of different types in a single meteorite, but had required modification when oxygen isotope data suggested that chondritic and achondritic materials were formed in different parts of the solar system. These isotope data also invalidated a lunar origin for the achondrites. Their formation in a body of small dimensions had been shown to be possible, as noted earlier, and opinion favoured origin in a body of asteroidal size, or in several asteroids of similar character. The absence of extreme shock effects in achondrites suggested low escape velocities associated with bodies smaller than the Moon, but some workers continued to advocate a body of lunar dimensions as the achondrite parent body. It had been recognized that brecciated achondrites resemble lunar regolith breccias in many respects, and probably originated in a similar manner. The presence in howardites of features such as glassy spherules (some with micrometeorite craters), track-rich grains and, in some instances, a content of primordial rare gas, all of which have analogues in the lunar soils and breccias, reinforced this conclusion. Consequently, the view that the achondrites had their origin in an asteroid (or asteroids) received support from the direct observation that the asteroid Vesta has a surface similar in composition to the basaltic achondrites.

Similar arguments applied to the parent body (or bodies) of the mesosiderites, and the same uncertainty exists over its dimensions. Oxygen isotope data do not rule out formation of the mesosiderites in the same parent body (or bodies) as the main classes of achondrites. The view at the end of the period considered appears to have been that the mesosiderites were formed in an asteroidal body in which segregation of metal and silicate phases was incomplete, and which had suffered disruption.

2.9.4 Achondrite ages

Consensus appears to have been reached in the period reviewed that the eucrites were formed about 4.55×10^9 years ago within a relatively short interval (4×10^6 years), this date having been determined by a variety of techniques (Pb-Pb, Rb-Sr, and Pb-U). K-Ar and U-He dating methods gave younger ages for the same class of meteorites. No ages for howardites and diogenites appear in the literature surveyed, and the only age quoted for a mesosiderite may not be reliable.

CHAPTER 3

COMPARATIVE PETROGRAPHY OF FIVE BRECCIATED ACHONDRITES

Comparisons are odorous.

William Shakespeare (1564-1616)

Much Ado About Nothing,

Act III, Scene V.

3.1 INTRODUCTION

The five achondrites studied petrographically (and by electron microprobe) are Binda, Bununu, Frankfort, Malvern, and Molteno (Table 1.1). Only Malvern and Molteno were obtained in a form that permitted macroscopic examination. These two meteorites are South African falls of fairly recent date, and neither has been comprehensively described. Some of the macroscopic features of Malvern have been reported by DESNOYERS and JÉROME (1977), and details of the morphology of Molteno appear in FROST (1971). The writer was able to examine Malvern in an almost complete form. Molteno could likewise be studied because half of the original stone is preserved in the meteorite collection of the Department of Geochemistry at U.C.T. Accordingly, brief macroscopic descriptions of both meteorites, together with some supplementary information, are recorded in this chapter.

The wider availability of samples of the other three meteorites has resulted in published descriptions of the circumstances of their discovery and of their macroscopic characteristics, and these data will not be repeated here. Information may be obtained from the following sources: Binda - ANDERSON and MINGAYE (1913), MASON (1974); Bununu - MASON (1967); Frankfort - MASON and WIIK (1966b).

3.1.1 Malvern - general information

The meteorite fell on the farm Malvern 335, 30 km south of Thaba Nchu ($29^{\circ}15'S$, $26^{\circ}50'E$), Orange Free State, South Africa, in 1933. It was found on 30th November, within an estimated 10 days of having fallen, by a Mr G. van Tonder, who presented it to the National Museum, Bloemfontein. The complete absence of terrestrial weathering in the meteorite supports its classification as a fall although its actual descent was not witnessed.

The original mass of the achondrite was not recorded (pers. comm., J.J. Oberholzer), but can be estimated at approximately 700 g from the amount of material now available for study. The bulk (about 590 g) remains in the National Museum as sample K1600. The Department of Geochemistry at U.C.T. has received samples totalling 81 g, of which 45 g remain intact. The British Museum acquired 9.8 g from the Cape Town sample, 2.3 g were donated to California Institute of Technology, and an estimated further 10 g were used in the U.S.A. and Austria in the preparation of the probe sections on which the present investigation is based. The U.S. National Museum has 19 g (HUTCHISON et al., 1977). The original mass of 10 kg given by JÉROME and CHRISTOPHE MICHEL-LÉVY (1971) is incorrect, and the source of the figure of 807 g quoted by FRICK and HAMMERBECK (1973) is unknown.

3.1.2 Molteno - general information

The Molteno howardite was seen to fall in 1953 by a Mr R.E. Trembath, who recovered one stone. The place and circumstances of the fall have been recorded by FROST (1971) and HUTCHISON et al. (1977). One half of the stone was presented to the British Museum in 1966. In 1973, with the kind assistance of a number of people in the Molteno district and in Cape Town, I succeeded in tracing Mr Trembath's widow in Berkshire, England. She kindly donated the half retained by her late husband to the Department of Geochemistry. The mass of this sample when received was 62 g.

3.2 MACROSCOPIC PETROGRAPHY

3.2.1 Malvern

In its original form, Malvern was roughly pear-shaped and measured about 10 cm across (Plate 3.1 A). The basic pear shape was modified by intersecting, slightly concave faces with thin ablation striae. The largest convex surface present was the frontal face during the fall, as shown by the directions of the striae and the development of a slight lip at its margins. The meteorite was covered with a very thin, lustrous, greenish-black fusion crust.

Sawn surfaces clearly reveal the fragmental character of the meteorite, which is an unsorted, unstratified polymict breccia composed of sharply angular and irregularly-shaped fragments that grade continuously from a maximum of 2.8 cm down to microscopic dimensions. The meteorite is well compacted and lithified, and shows no major fractures or veining. Its overall colour is pale grey, but many of the constituent fragments are very dark grey, almost black, with mineral and lithic inclusions of a lighter colour. Similar mineral and lithic clasts make up the bulk of the discernible material interstitial to the larger fragments. The majority of these clasts are less than 1 mm, but the largest observed - a lithic clast - measures 15 mm by 4 mm. A few very small lustrous grains of metal (or sulphide) occur both in the fine-grained interstitial material and in the dark fragments.

The most conspicuous fragment in the breccia is itself a breccia. It is roughly cubic, of 2.8 cm side, and is very pale grey (Plate 3.1 A). Of extremely fine grain, it contains angular grey clasts up to 4 mm in size and one subhedral green pyroxene crystal 7 mm across. Tiny grains of a black mineral are distributed throughout the pale 'matrix' of the fragment. No metal or sulphide grains were observed macroscopically in this micro-breccia.

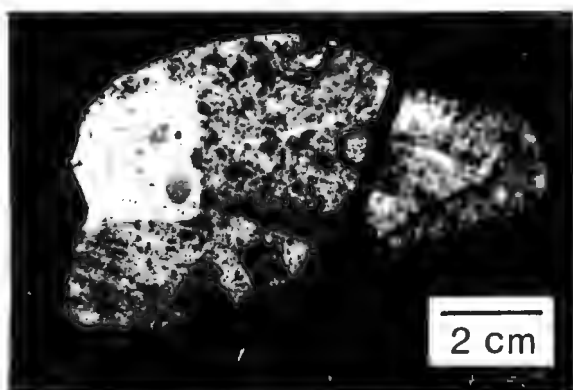
PLATE 3.1

- A. A partial reconstruction of the howardite Malvern from sawn fragments currently in the care of the National Museum, Bloemfontein. The photo clearly shows the fragmental character of the meteorite and the heterogeneity of its constituents. The pale clast at the left is the largest fragment in the specimen, the microbreccia described in the text. It contains large subhedral pyroxene inclusions and smaller opaques. The dark fragments in the body of the meteorite are glassy microbreccias. The angularity of many of the components is evident.
- B. The part of the howardite Molteno that is held by the Department of Geochemistry at U.C.T.; the scale is in cm. Its brecciated texture is not so obvious as is that of Malvern because most of the constituent fragments are similar in colour to one another and to the 'matrix'. The dark part in the lower right of the specimen is the fractured surface on which a secondary fusion crust has developed.

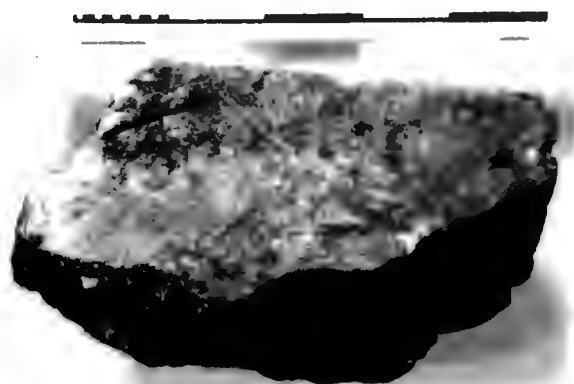
The remainder of this plate consists of photomicrographs of some of the thin sections studied. They were produced under identical conditions of magnification (shown by the scale bar) and illumination; plane polarized light was used. Each photomicrograph shows almost the entire thin section.

- C. Binda. The lighter areas of low relief are calcic plagioclases, while those of medium tone are pyroxenes. The darker material at the left of the photo is glassy. The coarse nature of the brecciation of this achondrite is evident.
- D. Bununu. The constituents of this howardite are far more finely comminuted than those of Binda. Pale brown glass in the section shows up as slightly darker irregular areas in the lower left and lower right of the photo.
- E. Frankfort. This meteorite shows a greater range of grain size than either Binda or Bununu. The majority of the clasts discernible in the photo are pyroxenes. The darkness of the 'matrix' material may be attributed partially to the relatively high proportion of chromite present in this howardite.
- F. Malvern. A typical section of this meteorite, showing subangular clasts of pyroxene and plagioclase, opaque minerals, fine 'matrix' materials, and irregular areas of dark glassy microbreccia containing abundant mineral inclusions, e.g. in the top left corner of the photo. The intrusive nature of the glassy microbreccia may be seen at the top centre.
- G. Malvern. This section shows the textural difference between typical parts of the meteorite and the large microbreccia clast referred to in the caption to Plate 3.1 A. Note that the finer-grained microbreccia, which occupies the top left part of the photo, is lithologically less diverse than the remainder of the meteorite.
- H. Molteno. This photo shows the wide range of grain sizes present in howarditic breccias. The 'matrix' is extremely fine, but it encloses relatively large fragments such as the pyroxene-plagioclase lithic clast at the right edge of the photo, and the pyroxene at upper left.

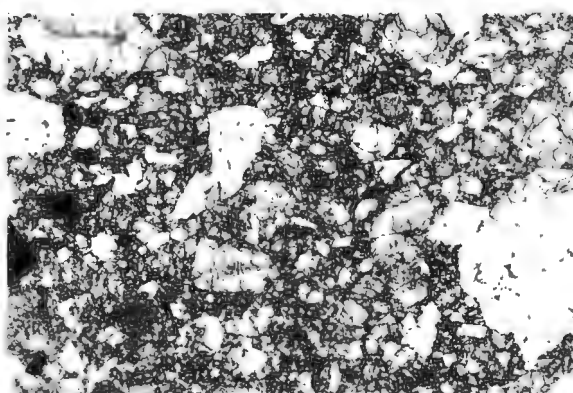
PLATE 3.1



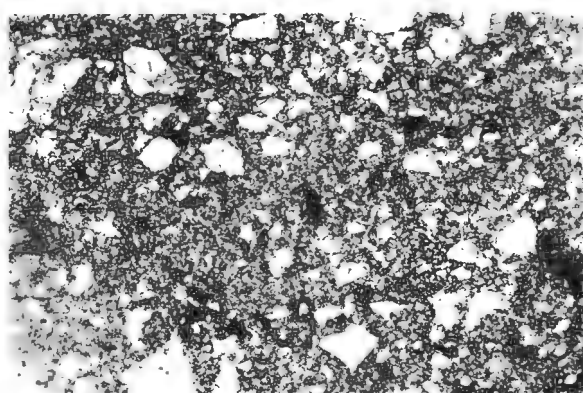
A



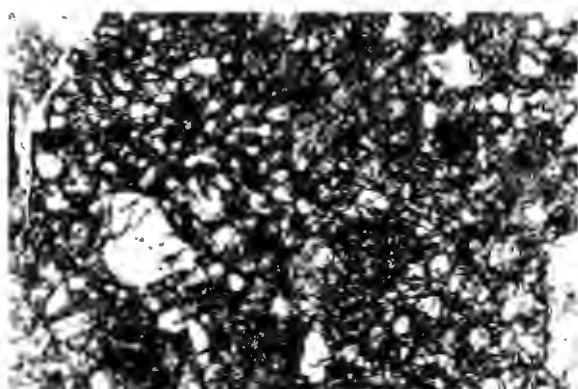
B



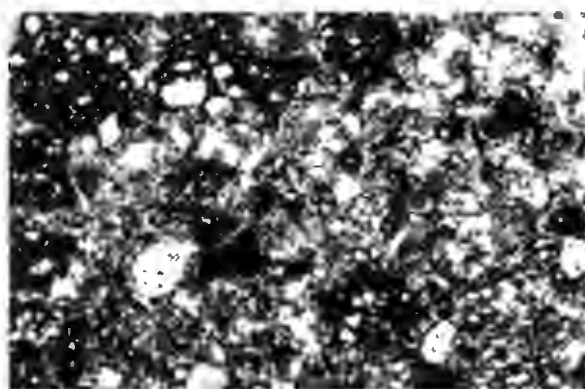
C



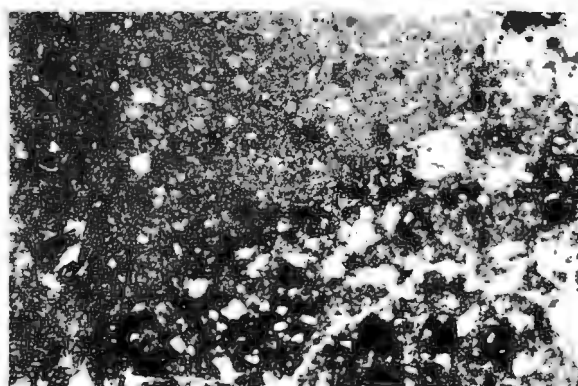
D



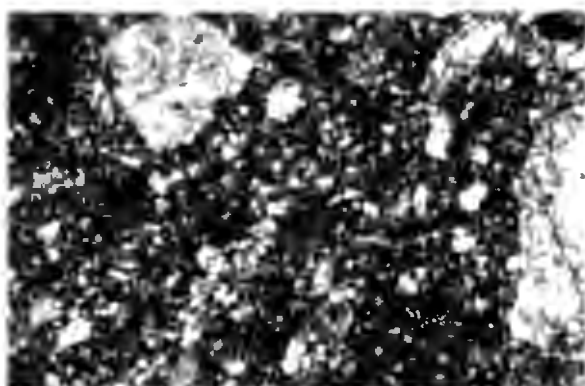
E



F



G



H

0.5 cm

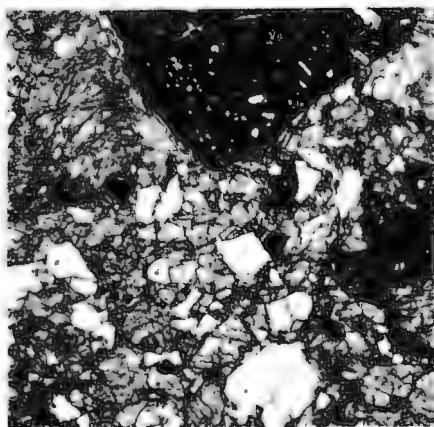
PLATE 3.2

The photomicrographs of Plates 3.2 and 3.3 were produced using plane polarized light and identical illumination and magnification, which (as shown by the scale bars) is higher than that of Plate 3.1.

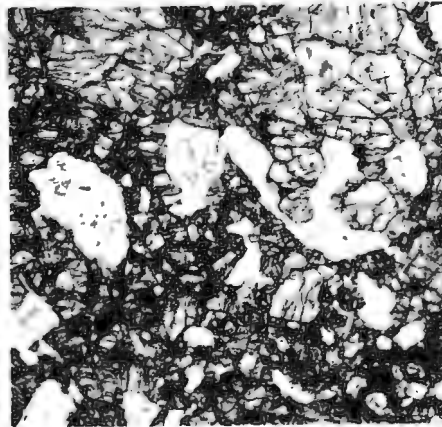
- A. Binda. An enlargement of an area in the centre of the left margin of Plate 3.1 C. The angular clasts of dark material are devitrified glassy microbreccias containing mineral inclusions. Note the extensive fracturing of the pyroxene crystals, in contrast to the relative absence of this feature in the plagioclases.
- B. Binda. The upper part of the photo is occupied by a single lithic clast composed of low-Ca pyroxene and anorthite in a possibly cumulate relationship. The opaque mineral in the clast is troilite. The enclosing 'matrix' lacks the high degree of comminution seen in the other achondrites studied.
- C. Binda. An enlargement of part of the large lithic clast that occupies the right margin of Plate 3.1 C. The texture resembles that of the lithic clast in the previous photo. Some of the pyroxene is optically continuous. The degree of fracturing of the anorthite is higher in this clast, as may be seen on the left of the photo.
- D. Binda. An enlargement of the remainder of the lithic clast described in C. It consists essentially of a single fractured crystal of anorthite with inclusions of troilite. Most of the remaining area of the photo is occupied by the chaotic assemblage of mineral and lithic debris that forms the bulk of the meteorite. As explained in the text, coarse lithic clasts such as those illustrated in B, C, and D are presumed to represent material that has survived the full effects of brecciation.
- E. Bununu. The irregularly-bounded mass of glass on the left margin of Plate 3.1 D may be seen in this photo to contain 'pockets' of the finely-communited material that surround it. The glass is shattered, but shows no devitrification features other than spherulitic extinction (see Plate 3.4 D). It contains no mineral inclusions (the clear areas are holes in the section).
- F. Bununu. The clasts illustrated are among the largest present in the section, and are of pyroxene of various compositions. The badly fractured clast near the centre of the photo is compositionally nearly identical to the almost unfractured grain at top centre. The opaque minerals are chromite.
- G. Bununu. The top left portion of this photo is occupied by an irregular fragment of glassy microbreccia containing sparse inclusions of pyroxene and plagioclase. The glassy matrix shows extensive devitrification. The elongate clast at the bottom margin is composed of Ca-poor pyroxene, and has a cataclastic texture.
- H. Bununu. This photo shows the finely comminuted nature of the 'matrix' of this howardite in comparison with that of Binda (see, for example, photos B and D of this plate). The angular clast at the lower right of this photo is an extremely fine-grained recrystallized mosaic of low-Ca lamellar pyroxene crystals that contains also a few patches of recrystallized plagioclase.

PLATE 3.2

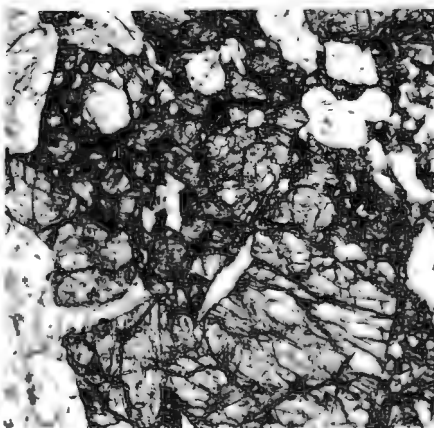
A



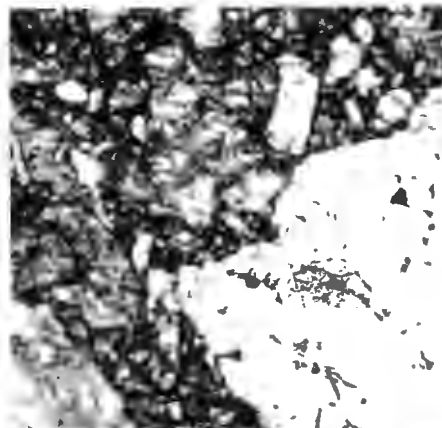
B



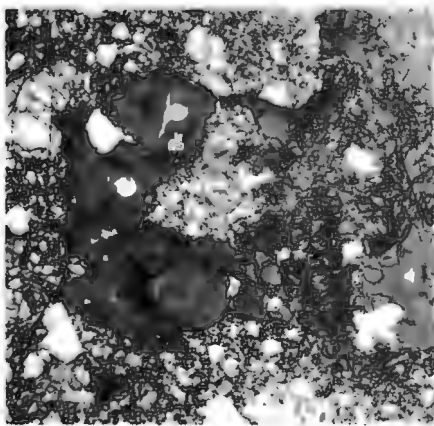
C



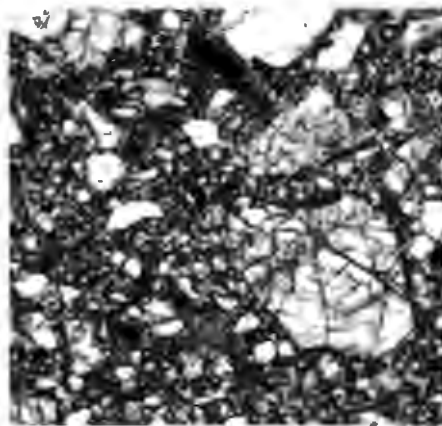
D



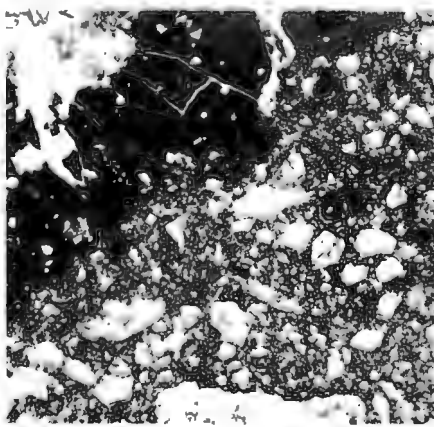
E



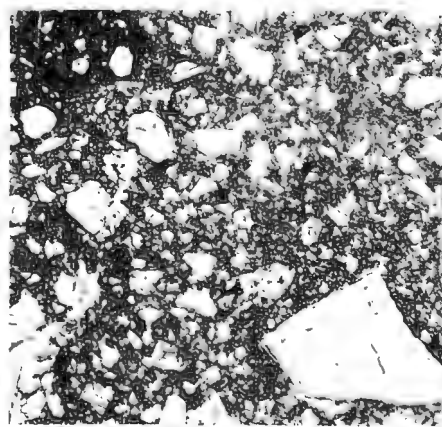
F



G



H



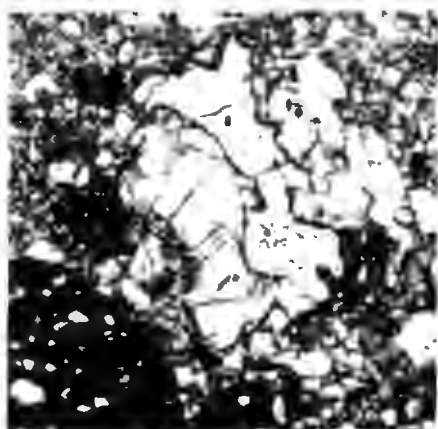
1 mm

PLATE 3.3

- A. Malvern. The lithic clast depicted consists of Ca-poor pyroxene and partially-devitrified plagioclase glass (maskelynite) with the composition of anorthite (see also Plate 3.5 G and H). The adjacent dark clasts are glassy microbreccias with abundant inclusions, mainly of pyroxene.
- B. Malvern. An enlargement of part of Plate 3.1 F, showing the heterogeneity of the constituents and the continuous gradation in grain size. The large euhedral inclusion in one of the dark glassy microbreccia fragments is a low-Ca pyroxene. The central part of the left half of the photo is occupied by a plagioclase-pyroxene clast partially replaced by disseminated troilite.
- C. Malvern. The lithic clast that occupies most of this photo is composed of magnesian pigeonite and laths of bytownite in an ophitic relationship. Ilmenite occurs in accessory amounts. The angular clast to the right is of orthopyroxene.
- D. Malvern. A variety of clast types, and the fine 'matrix' in which they occur, are illustrated in this photo. The dark area at the top is devitrified glass, while those in the centre are glassy microbreccias with mineral inclusions. The lower half of the photo contains part of a lithic clast with a cumulate texture. It is composed of Ca-poor pyroxene and plagioclase.
- E. Molteno. The dark mass in the lower part of this photo is a large grain of metal, roughly circular in outline, that contains inclusions of 'matrix' material and pyroxene clasts. In the top right of the photo is a dark glassy microbreccia similar to those seen in Malvern (e.g. photo A of this plate).
- F. Molteno. Mineral, lithic, and devitrified glass clasts all occur in the part of the howardite illustrated, and the high degree of comminution of the constituents is evident. Material very tentatively regarded as chondritic is present towards the top left corner of the photo.
- G. Molteno. The large clast in the left of the photo is a pyroxene-plagioclase cumulate that has undergone severe cataclasis, with subsequent annealing. It has been completely broken through; the fracture may be seen in the lower left corner. The other large fragment is composed of dark brown glassy microbreccia with abundant inclusions of pyroxene and plagioclase (cf. photos A and E of this plate).
- H. Molteno. The dark coloration of the 'matrix' material in this part of the meteorite appears to be due to the extensive crushing it has undergone. Post-consolidation movement is indicated by the fracture that runs diagonally from the top right corner of the photo. The opaques are chromite and metal.

PLATE 3.3

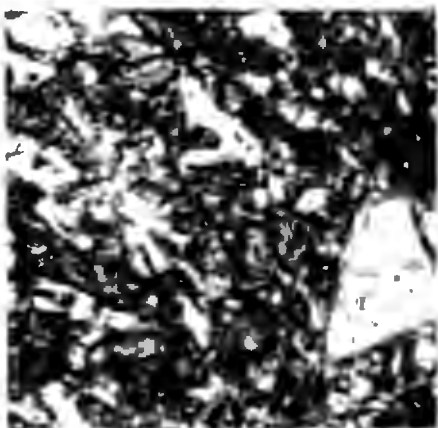
A



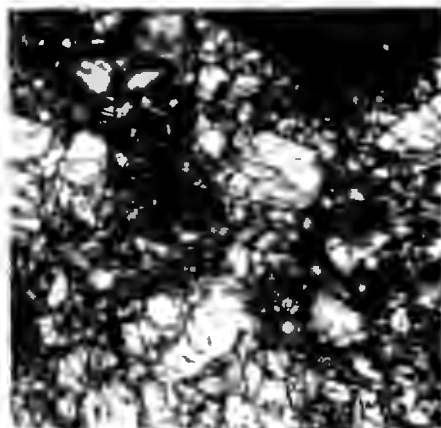
B



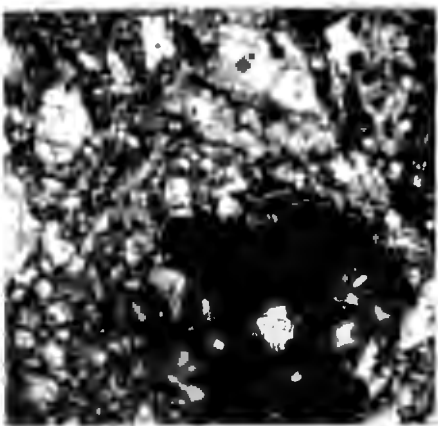
C



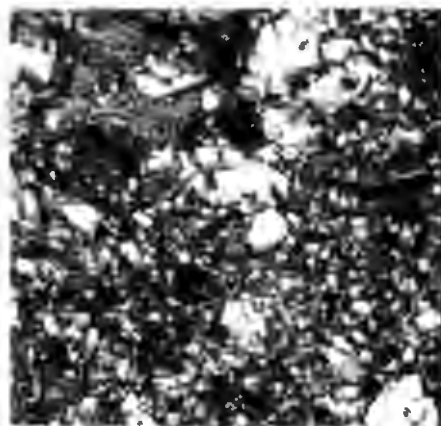
D



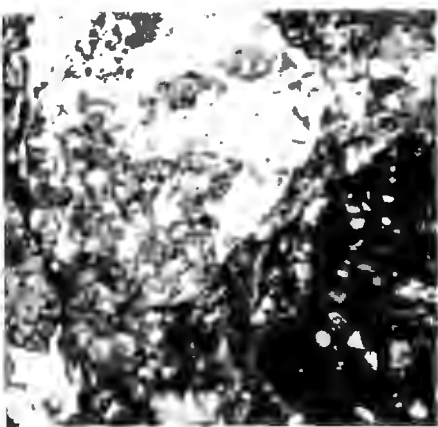
E



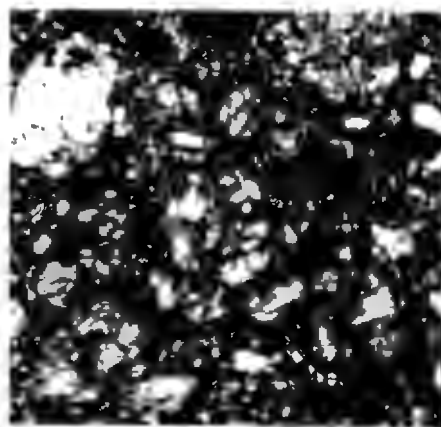
F



G



H



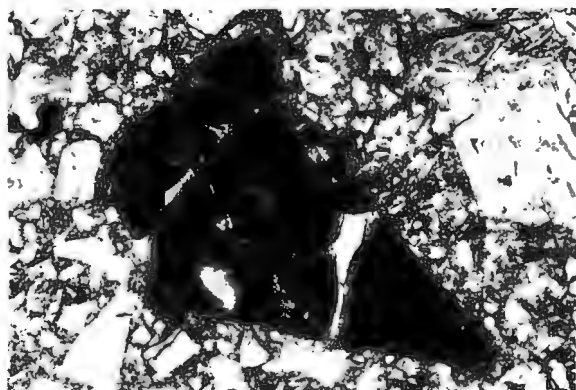
1 mm

PLATE 3.4

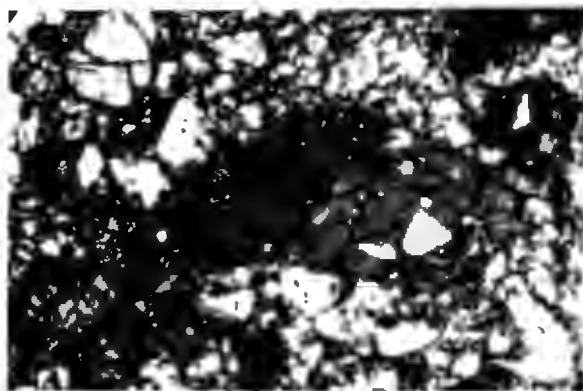
GLASSES IN THE ACHONDRITES STUDIED

- A. Bununu. A clast of pale brown glass with smooth, slightly arcuate boundaries and a few minor fractures. The dark spots may be centres of incipient devitrification, but the glass is completely isotropic. The only included material is a small plagioclase clast in the lower left of the fragment. Plane polarized light. Magnification 100 times.
- B. Malvern. A glassy clast of material very similar to that described above. Its arcuate outline and fracture pattern suggest flow. It has incorporated more material than the Bununu example; the inclusions are mainly anorthite, but some pyroxene is present. The glass is completely isotropic. Plane polarized light. Magnification 40 times.
- C. Bununu. Part of the large, irregular body of glass shown in Plate 3.2 E. It is pale brownish-orange, and differs from the glasses described above in having neither inclusions nor dark spots, and in being locally extensively shattered and comminuted. Part of the 'pocket' of groundmass surrounded by this glass may be seen at the bottom of the photo. Plane polarized light. Magnification 100 times.
- D. Bununu. As for C, but with crossed polars. This glass is not isotropic, as are the examples in A and B, but exhibits very well developed spherulitic extinction, which may be an indication of incipient devitrification.
- E. Malvern. An angular clast of almost black glass of unusual composition (see text) that is crowded with large skeletal crystals of stumpy habit. Only the outlines of these phenocrysts are discernible; their interiors appear to be at least partially glassy. This is the only representative of this lithological type in the achondrites studied. Plane polarized light. Magnification 40 times.
- F. Malvern. A clast of pale brown glass of similar type to those depicted in A and B above. It is completely isotropic, but contains the characteristic dark spots that may indicate incipient devitrification. It is free of inclusions. The shape of the clast suggests it is part of an originally spherical droplet. Plane polarized light. Magnification 100 times.
- G. Malvern. A pale yellowish, perfectly spherical glassy droplet with concentric zonation defined by an aggregation of minute dark brown particles. A very narrow peripheral zone exhibits faint anisotropism. Plane polarized light. Magnification 100 times.
- H. Malvern. Another possible glassy droplet, brownish-orange in colour and devoid of inclusions. Plumose texture indicates partial devitrification, and the material shows definite anisotropism. It is compositionally different from the usual glass present in this howardite (e.g. B and F of this plate), and may be of chondritic origin. Plane polarized light. Magnification 100 times.

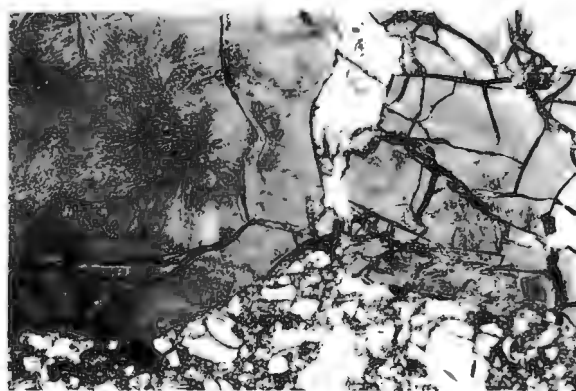
PLATE 3.4



A



B



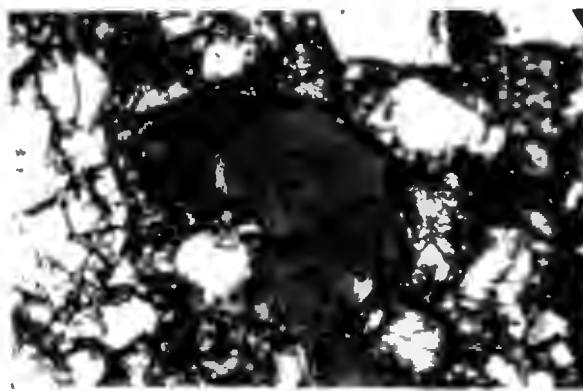
C



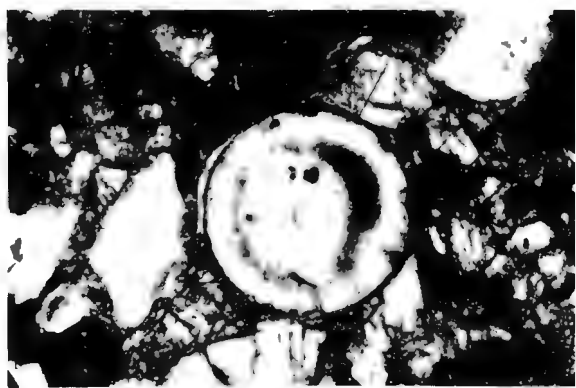
D



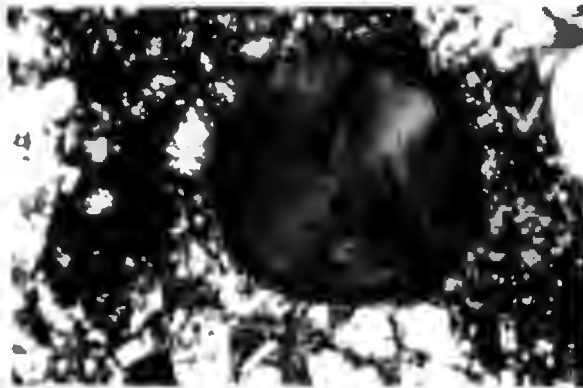
E



F



G



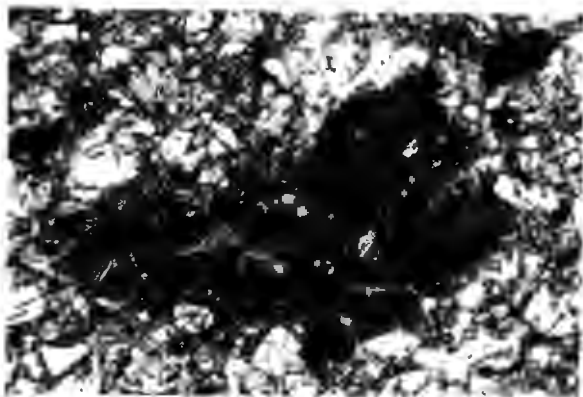
H

PLATE 3.5

DEVITRIFIED GLASSES AND GLASSY MICROBRECCIAS

- A. Molteno. An angular clast of brownish glass of a type characteristic of this howardite. The glassy matrix is isotropic, but is not clear (cf. the example of Plate 3.4) because of the concentration of minute crystallites (quench crystals) in it. The fragment contains many inclusions of 'matrix' minerals also. Plane polarized light. Magnification 100 times.
- B. Binda. Detail of the largest clast of glassy microbreccia present in this achondrite (see also Plate 3.2 A). The matrix has devitrified completely to a pale grey cryptocrystalline aggregate that surrounds the abundant mineral inclusions. The two smaller microbreccia fragments in the photo are of similar type. Plane polarized light. Magnification 40 times.
- C. Bununu. Completely devitrified glassy microbreccia, very similar to that described in B. The upper part of the fragment is pyroxene, the remnant of an inclusion in the microbreccia. Smaller pyroxene inclusions are visible in the devitrified matrix. Plane polarized light. Magnification 100 times.
- D. Frankfort. Grey devitrified material similar to the Binda and Bununu examples enclosing euhedral laths of twinned plagioclase. Plane polarized light. Magnification 100 times.
- E. Malvern. An angular clast, lying within the fine-grained microbreccia fragment illustrated in Plate 3.1 A and G, that contains randomly orientated relics of pyroxene phenocrysts in a pale grey devitrified matrix. Presumably this matrix material, and that described from the Frankfort example above, represent devitrified glassy mesotaxis in originally vitrophyric lava clasts. Plane polarized light. Magnification 40 times.
- F. Binda. A devitrified microbreccia clast of the type illustrated in B that has been compressed between two plagioclase clasts. With crossed polars (see Plate 3.7 C), deformation and microfaulting of the twin lamellae of the larger feldspar, and the development of shock lamellae, are visible. The microbreccia clast itself has sheared parallel to the longer axis of the photo. Plane polarized light. Magnification 40 times.
- G. Malvern. Part of the clast illustrated in Plate 3.3 A enlarged to show the reaction rims, which appear to be of a symplectitic texture, present at the contact between orthopyroxene and devitrified maskelynite. Plane polarized light. Magnification 100 times.
- H. Malvern. As for G, but with crossed polars. The devitrified maskelynite presents a fine-grained mosaic appearance, with the individuals in the mosaic arranged in whorl-like masses. Similar material has been reported from lunar breccias (see text).

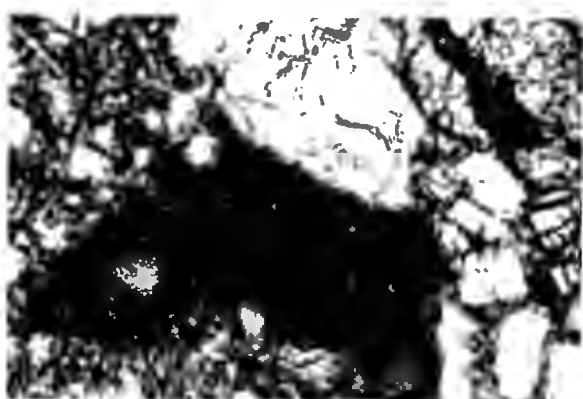
PLATE 3.5



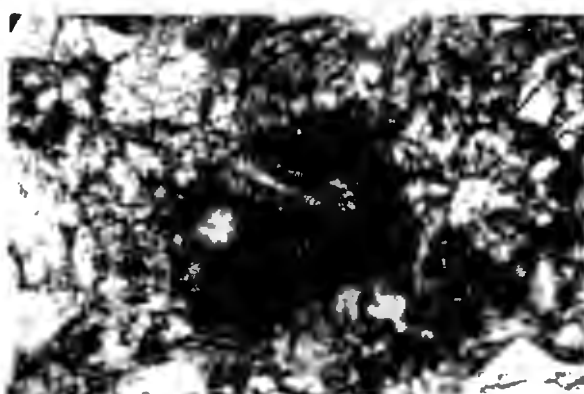
A



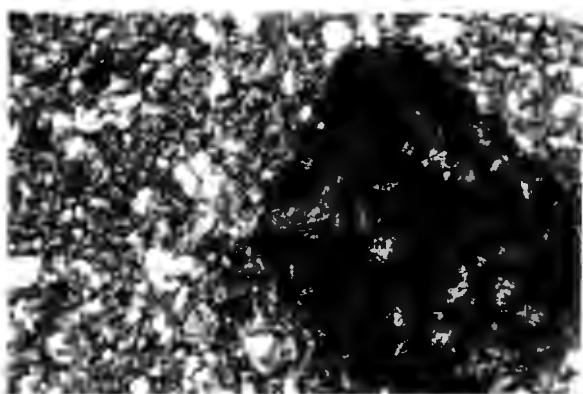
B



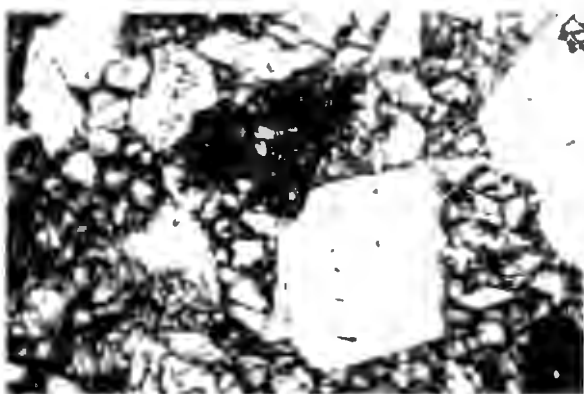
C



D



E



F



G



H

PLATE 3.6

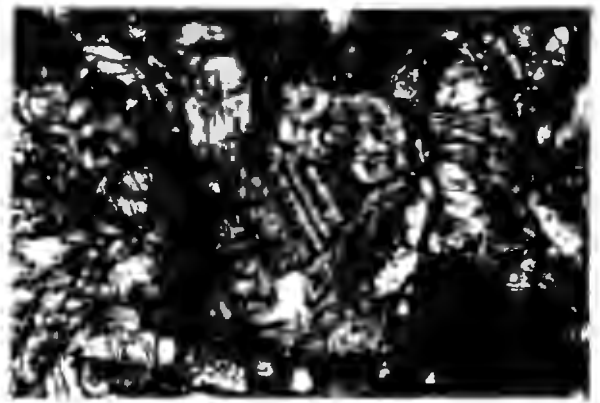
'COARSE-GRAINED' LITHIC CLASTS

- A. Frankfort. The central part of the photo is occupied by a typical lithic clast with sup-ophitic texture. The constituent minerals are bytownite and intermediate pigeonite, with accessory ilmenite. The pigeonite shows broad exsolution lamellae of ferroaugite. The upper part of the photo depicts finely comminuted 'matrix', while part of a large clast of orthopyroxene is situated in the lower left corner. Plane polarized light. Magnification 40 times.
- B. Frankfort. As for A, but with crossed polars. The broad exsolution lamellae in the pigeonite in the centre of the photo are clearly displayed.
- C. Malvern. Part of a large pyroxene-plagioclase clast with ophitic texture. The fragment has undergone some cataclastic deformation. It is traversed by several glass-filled fractures, the most prominent of which appears as a curved line running vertically through the area photographed. A zone of crushing lies to the right of this fracture. Plane polarized light. Magnification 40 times.
- D. Malvern. As for C, but with crossed polars. The finely-crushed material in the zone of cataclasis is clearly visible. Both pyroxene and plagioclase have been involved in the crushing.
- E. Molteno. Part of a large pyroxene-plagioclase clast. The original igneous texture has been obliterated by brecciation in most of the clast, but 'islands' such as that illustrated remain, showing that the original rock had an ophitic texture. The dark material at the lower left of the photo is the 'matrix' surrounding the partially-brecciated lithic clast. Plane polarized light. Magnification 40 times.
- F. Molteno. As for E, but with crossed polars.
- G. Molteno. Part of a large lithic clast composed essentially of low-Ca pigeonite and bytownite (An_{83}), but containing also some orthopyroxene crystals. The clast exhibits two distinct types of texture. One is dominated by large masses of pyroxene (mainly pigeonite with prominent exsolution lamellae). Between these are areas in which small granular pigeonites are poikilitically enclosed in large plagioclase plates that show a moderate degree of preferred orientation. This textural type occupies the central part of the photo. It is thought to indicate partial recrystallization of the original igneous rock (see text). The opaque grains are intergrowths of chromite and ilmenite. Plane polarized light. Magnification 40 times.
- H. Bununu. Part of a lithic fragment consisting of an aggregate of bytownite (An_{84}) crystals and the twinned crystal of sub-calcic ferroaugite illustrated. This pyroxene contains abundant Schiller inclusions, the major set of which are symmetrically disposed to the twin plane. A minor set maintains its orientation across the twin plane (i.e. northeast to southwest in the photo), and evidently post-dates the twinning. Plane polarized light. Magnification 100 times.

PLATE 3.6



A



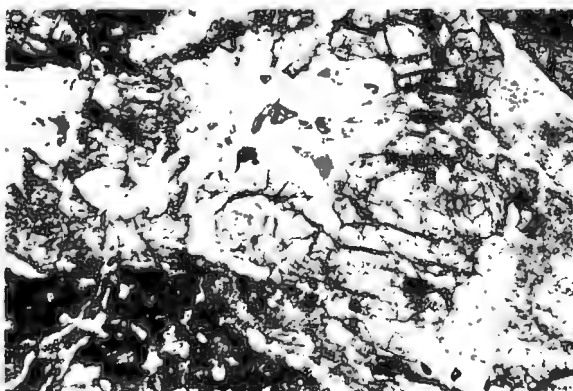
B



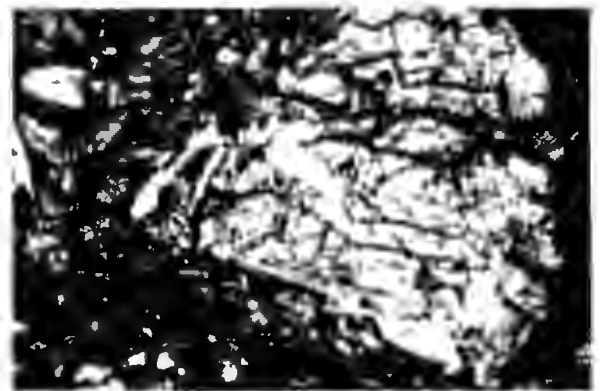
C



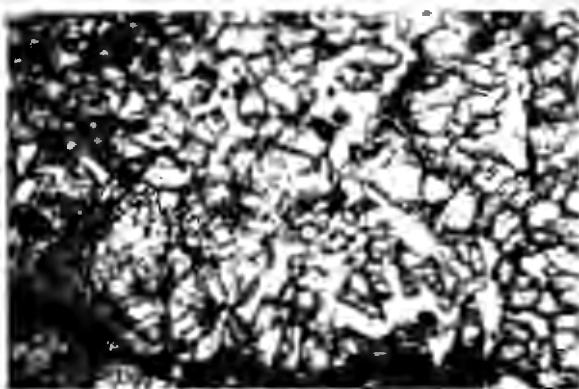
D



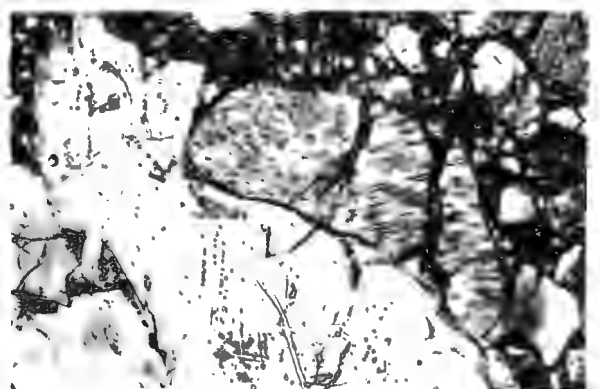
E



F



G



H

PLATE 3.7

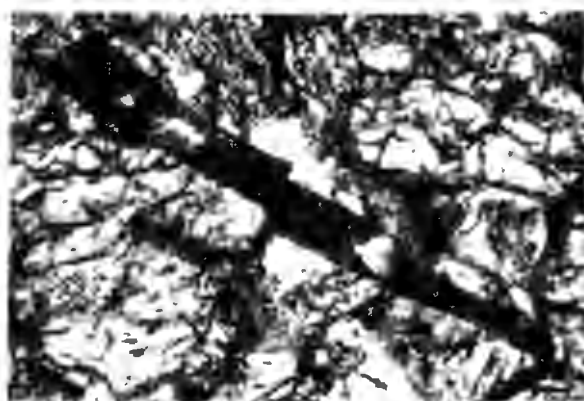
SHOCK FEATURES

- A. Binda. Severe fracturing of a large anorthite clast is made evident by microfaulting of the twin lamellae. Much of the damage has been caused by pressure exerted on the crystal by surrounding material, e.g. the wedge-shaped block in the centre of the photo has been displaced by these means. Elsewhere, a pyroxene clast impinges on the clast and has produced fracturing and crushing. The shock undergone by the crystal has resulted in very irregular extinction relationships. Crossed polars. Magnification 40 times.
- B. Binda. Pale grey devitrified glass filling a fracture in an orthopyroxene clast has been microfaulted by later movements that have produced cross-fracturing in the pyroxene. Plane polarized light. Magnification 100 times.
- C. Binda. The anorthite crystal clast illustrated in Plate 3.5 F, showing the deformation and fracturing effects produced by pressure from the adjacent devitrified glassy clast. The shock lamellae developed traverse the clast in a vertical direction in the photo. Crossed polars. Magnification 40 times.
- D. Frankfort. The extensive fracture system in the large orthopyroxene clast illustrated has been filled by glass, presumably impact-produced. The fine exsolution lamellae have been displaced by the fracturing, and the birefringence of the crystal is very patchy. Crossed polars. Magnification 40 times.
- E. Binda. Large, sub-rounded anorthite clast with very patchy and irregular extinction resulting from shock. Some crushing is present at points of contact with adjacent plagioclase clasts (to the left) and pyroxene fragments (to the right). A fracture developed in the pyroxene at the right edge of the photo runs into the shocked anorthite clast. Crossed polars. Magnification 40 times.
- F. Binda. Extensively fractured euhedral anorthite crystal in a large pyroxene-plagioclase clast. Numerous dislocations of the twin lamellae may be seen, and the extinction pattern of the crystal is very irregular because of the structural damage suffered. Crossed polars. Magnification 40 times.
- G. Malvern. Fractured and shocked anorthite clast in which shock lamellae are well developed. They run roughly parallel to the long axis of the photo, transverse to the twin lamellae. (The single diagonal line is a surface scratch.) Crossed polars. Magnification 100 times.
- H. Bununu. In contrast to the other achondrites studied, and despite the high degree of comminution of its constituents, Bununu contains a greater proportion of clasts that show little effect of shock. The plagioclase illustrated is typical. Apart from some minor fracturing, it shows no effects of shock associated with brecciation, and has completely normal extinction characteristics. Crossed polars. Magnification 100 times.

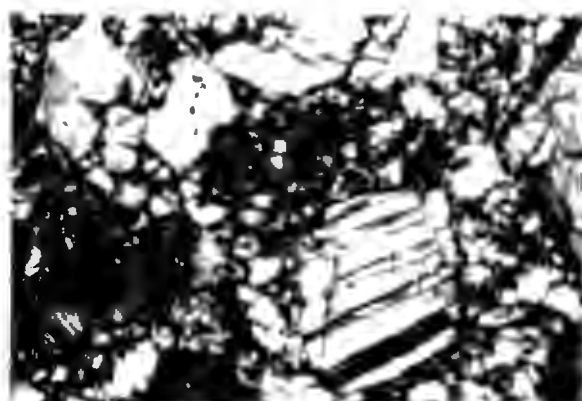
PLATE 3.7



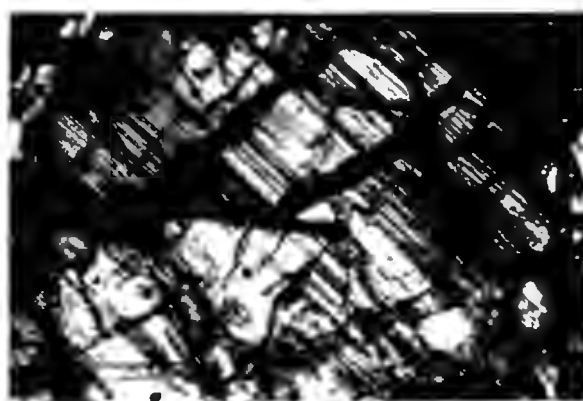
A



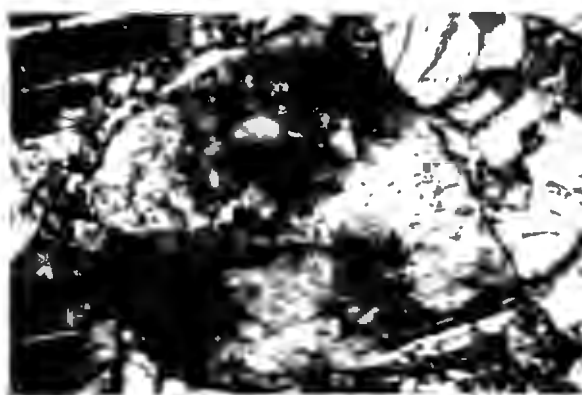
B



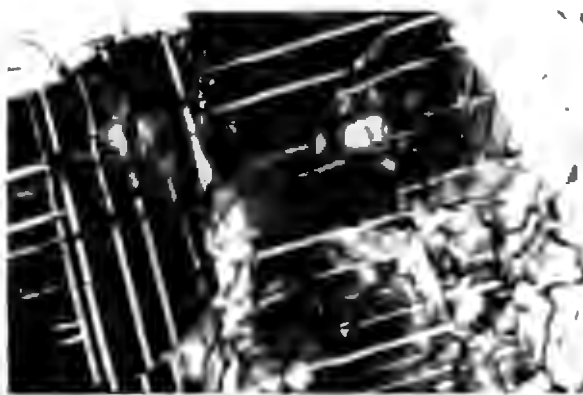
C



D



E



F



G



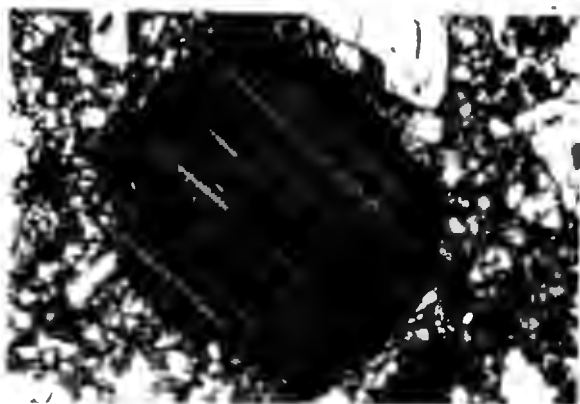
H

PLATE 3.8

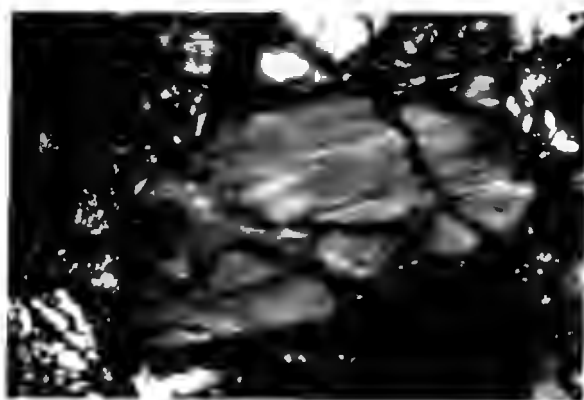
EXSOLUTION FEATURES IN PYROXENES

- A. Bununu. Approximately euhedral clast of orthopyroxene with extremely fine but regular exsolution lamellae. The bulk composition of this clast includes only 0.91% CaO. Crossed polars. Magnification 40 times.
- B. Malvern. Fractured subhedral orthopyroxene clast, also showing extremely fine exsolution. In this instance, however, the exsolved phase does not form continuous lamellae (cf. A above), but occurs as interlocking, elongate, spindle-shaped blebs with a common orientation in the crystal. Crossed polars. Magnification 100 times.
- C. Binda. A pyroxene clast showing extensive cross-fracturing and coarse, irregularly-shaped exsolution lamellae. The host is a Ca-poor orthopyroxene, while the exsolved phase is augite. Plane polarized light. Magnification 100 times.
- D. Binda. As for C, but with crossed polars.
- E. Binda. A shattered, subhedral clast of orthopyroxene in which the 'spindly' type of exsolution is more clearly developed than in the Malvern example above (B). Crossed polars. Magnification 40 times.
- F. Bununu. Small lithic clast included in a devitrified glassy microbreccia. The bulk of the fragment appears to be made up of a single, multiply-twinned orthopyroxene crystal that has exsolved a Ca-rich phase in two distinct stages. A discontinuous set of exsolved blebs parallels the cleavage direction (which is followed also by trains of tiny opaque inclusions). This set is crossed obliquely by a set of thinner, but more regular and continuous, lamellae that give a crenellated appearance to the twin plane in the centre of the photo. Crossed polars. Magnification 100 times.
- G. Bununu. A shattered lithic clast in the matrix composed mainly of a pyroxene crystal that displays two sets of exsolution lamellae. The host (the broad, dark lamellae in the photo) is an orthopyroxene, and the main set of exsolution lamellae, running parallel to the cleavage, are augitic. A second, more poorly developed set of lamellae occur in the host areas; these minor lamellae are roughly parallel to the longer axis of the photo. In places they appear to be optically continuous with the main exsolved phase. Crossed polars. Magnification 40 times.
- H. Bununu. A twinned low-Ca pyroxene in a lithic clast that exhibits complex exsolution. The main exsolved lamellae are parallel to the twin plane and, although patchy and of variable width, are more or less continuous. A poorly-developed second set of fine, discontinuous lamellae crosses the first set obliquely. These are symmetrically disposed to the twin plane, and are paralleled in places by fine Schiller inclusions. Crossed polars. Magnification 100 times.

PLATE 3.8



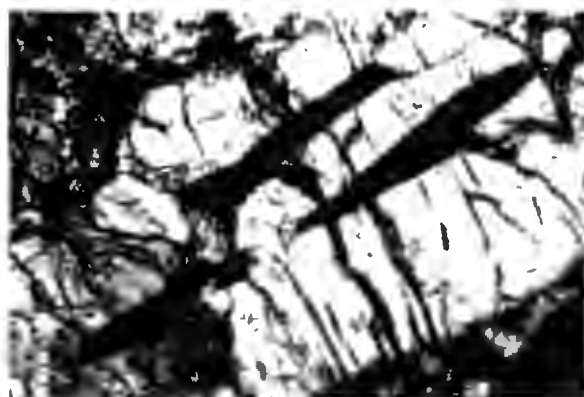
A



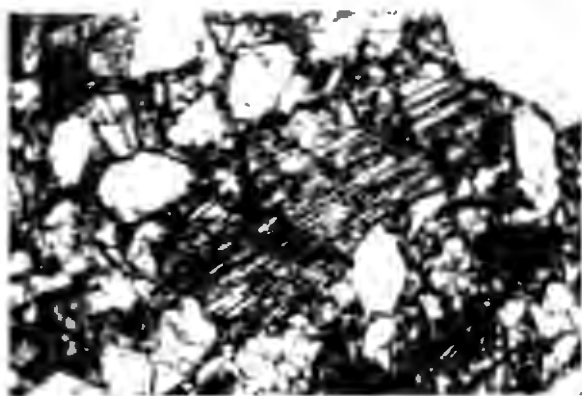
B



C



D



E



F



G



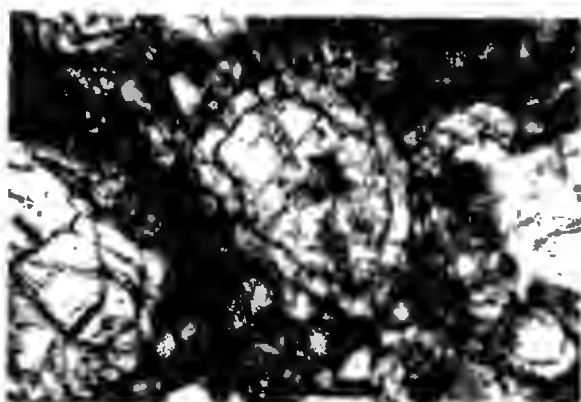
H

PLATE 3.9

MISCELLANEOUS FEATURES

- A. Frankfort. A sub-rounded body of indeterminate mineralogical composition; the microprobe indicated the presence of major Si, with minor Ca and Al. The finely crystalline rim appears to be of similar composition. This clast is interpreted as a rimmed chondrule, and is the only constituent of possible chondritic origin observed in this howardite. Plane polarized light. Magnification 100 times.
- B. Frankfort. As for A, but with crossed polars.
- C. Malvern. A sub-angular clast consisting of an aggregate of radiating laths of brownish orthopyroxene with a composition different from those normally encountered in the low-Ca pyroxenes in this meteorite. The clast is regarded as part of a chondrule, the only such material identified in Malvern. Plane polarized light. Magnification 40 times.
- D. Binda. A thin fusion crust of greenish-yellow glass is present in places in the section studied. The crust contains abundant spherical bubbles, some filled with dark opaque material, and some partially-fused remnants of refractory ore minerals (not shown in the photo). Plane polarized light. Magnification 100 times.
- E. Binda. Tridymite partially replacing twin lamellae in a deformed crystal of anorthite in a lithic clast. The silica minerals contain tiny needle-like inclusions, possibly of rutile. The mineral in the lower left corner of the photo that also partially replaces the lamella occupied by the larger tridymite crystal is pyroxene. Plane polarized light. Magnification 40 times.
- F. Binda. As for E, but with crossed polars.
- G. Malvern. A small lithic clast consisting of anorthite and pigeonite that is surrounded by a narrow rim of dark brown glass. Several such fragments were noted in the meteorite. They may formerly have been inclusions in glassy microbreccias disrupted by further impact and brecciation. Plane polarized light. Magnification 40 times.
- H. Bununu. A lithic fragment that has been partially replaced by a sponge-like mass of troilite, in the interstices of which small plagioclase laths may be distinguished. The sulphide may have selectively replaced the bulk of the original pyroxene. The presence of large plagioclase crystals (e.g. lower left of the photo) suggests the original texture may have been porphyritic. Plane polarized light. Magnification 100 times.

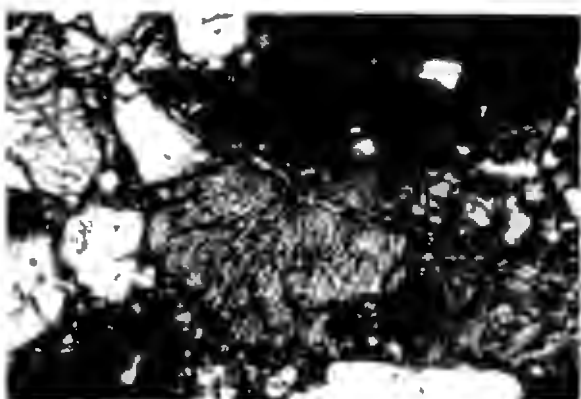
PLATE 3.9



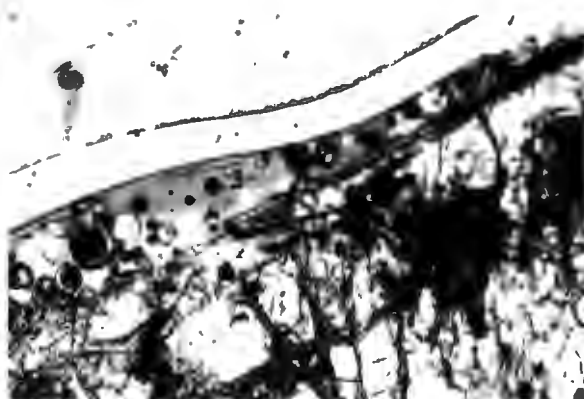
A



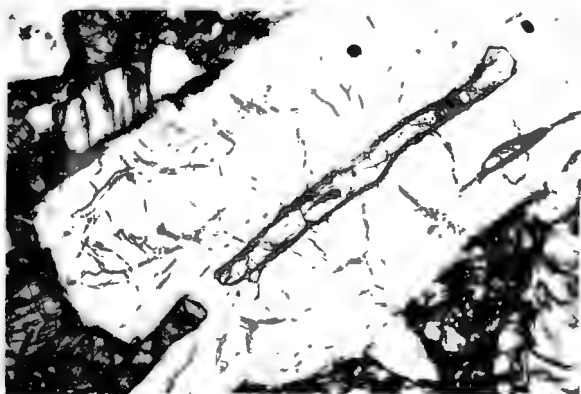
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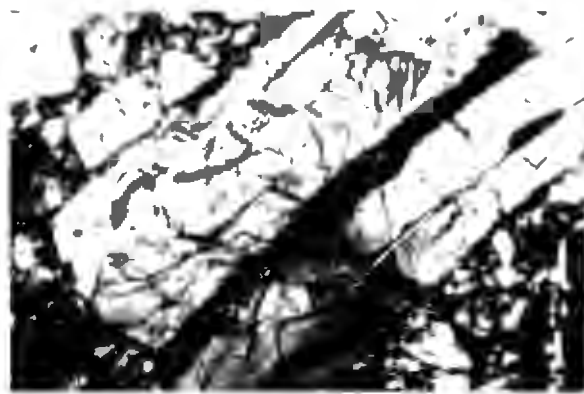
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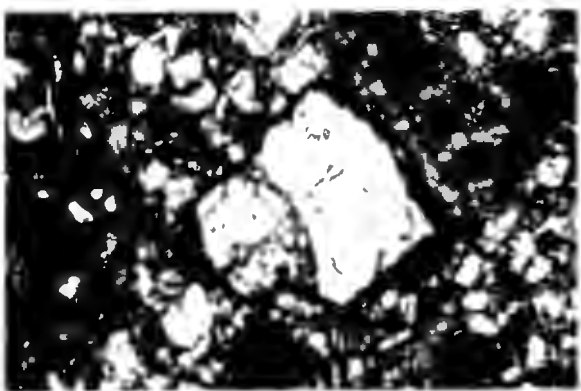
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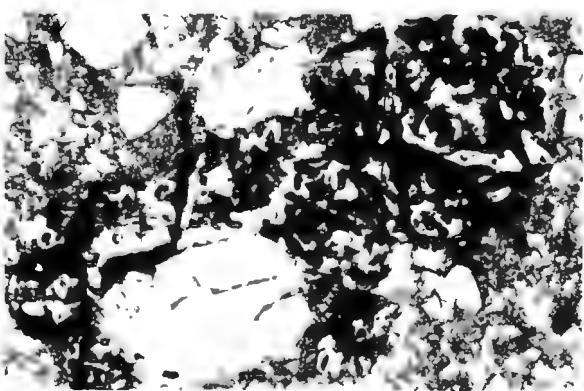
E



F



G



H

3.2.2 Molteno

The Cape Town sample of Molteno has a maximum dimension of 60 mm (Plate 3.1 B). A finely-striated fusion crust is present on the two original smooth faces preserved. This crust is similar to that of Malvern, but is thinner, with a discontinuous distribution of dark lustrous patches. A secondary fusion crust developed on a large irregularly-fractured surface points to disruption of the original meteorite in its deceleration phase in the atmosphere.

Macroscopic examination of sawn surfaces shows that Molteno, like Malvern, is a well-compacted polymict breccia. The meteorite shows the same continuous gradation in fragment size noted in Malvern, and a similar lack of stratification. The largest fragment present in the sample has a maximum dimension of about 12 mm. The fragments are mostly medium grey, and are not as easily discernible as those of Malvern because the fine-grained interstitial material is only very slightly darker. A number of dark grey clasts are present, but the amount of dark material is much less than in Malvern (cf. A and B, Plate 3.1). Irregularly-shaped fragments are less common than in Malvern; most of the constituents in Molteno are angular. Fewer lithic clasts of possible eucritic origin occur in Molteno. The largest of these observed is about 5 mm long. No fragments of microbreccia conspicuously different in appearance from the remainder of the meteorite breccia, such as that described in Malvern, were noted in Molteno. Lustrous specks of sulphide and metal appear to be more abundant in Molteno and, although they occur also within the fragments, they show a tendency towards concentration along grain boundaries.

3.3 MICROSCOPIC PETROGRAPHY.

The terminology employed in this section is in accordance with the

Glossary of Lunar Terms (Proceedings of the Fifth Lunar Science Conference, 1974). Furthermore, an attempt is made to minimize the confusion caused by the different nomenclature used for orthopyroxenes by petrologists and by meteoriticists (KEIL, 1969). Orthorhombic pyroxenes are referred to merely as 'orthopyroxenes', and the term 'diogenite' is used in preference to 'hypersthene achondrite'.

In the investigation of the five achondrites, emphasis was placed on obtaining data on the chemical compositions of their constituent phases for use in conjunction with their bulk compositions. Their microscopic petrography was therefore not the subject of exhaustive study (e.g. by universal stage techniques), but was directed at providing adequate basic data to facilitate understanding and interpretation of the compositions of the various components present, and to help to derive the formational history of the meteorites.

3.3.1 Textural features

All five achondrites studied are brecciated. All but Binda, which will be considered later, are clearly polymict. None show any sorting or stratification of their constituent fragments. The continuity of grain-size variation observed macroscopically in Malvern and Molteno is present on a microscopic scale also in all five achondrites. Comparison of the textures of the five meteorites may be made from low-magnification photomicrographs of some of the thin sections studied (Plate 3.1 C - H). These are reproduced on a common scale, and represent almost the complete section in each instance. Although systematic study of grain-size distribution was not included in the present investigation, it is obvious from these photos that such distributions are markedly different in the achondrites illustrated. Similar variability in particle-size distribution is evident in the howardites Kapoeta and

Bholghati, depicted in Fig. 1 A and B of BUNCH (1975). Qualitatively, it may be observed that, of the achondrites included in the present study, Binda (Plate 3.1 C) contains the highest proportion of coarse mineral constituents and relatively little comminuted 'matrix', but Malvern (Plate 3.1 F and G) incorporates the largest clasts of brecciated and glassy material. On the other hand, Bununu (Plate 3.1 D) and Frankfort (Plate 3.1 E) contain high proportions of finely-comminuted material, as do parts of Molteno (Plate 3.1 H - the central area, for instance). The problems arising from the extremely heterogeneous character of these meteorites, even on a scale of millimetres, must continually be taken into account in their sampling and analysis, and in the interpretation of petrographic and chemical data derived from samples, especially those of small size.

The photomicrographs of Plate 3.1 emphasize the very fine-grained nature of these five brecciated achondrites. Only exceptionally do constituents exceed 2 mm, and the vast majority of fragments are measureable on a scale of hundreds, or even tens, of microns. This must be borne in mind wherever terms such as 'coarse-grained' appear in this report.

Plates 3.2 and 3.3 show, in greater detail, some of the textural features noted in Plate 3.1 C-H. The magnification is constant throughout this series of photomicrographs to facilitate comparison of these features.

Most of the components of the meteorite breccias are angular to sub-angular. Rounded or sub-rounded boundaries are rare in the mineral and lithic clasts, but are present in some of the glassy materials. These, however, generally exhibit irregular outlines and may even be difficult to distinguish from the finely-comminuted material in which they occur. Arcuate fractures are present in both mineral and glassy materials, but are not common.

Post-consolidation fracturing and movement have taken place in

Frankfort and Molteno (Plate 3.3 H), and to a lesser extent in Malvern. These effects are very slight, and are revealed by poorly-defined fractures that traverse the sections for distances of several millimetres. In places, these fractures appear to have been filled by glassy material or minute amounts of an opaque mineral. Indications of other, even smaller, dislocational movements, e.g. in situ disruption and micro-faulting of individual clasts, will be described in later sections.

3.3.2 The constituents of the achondrites studied

The dominant components of all five meteorites are pyroxene and plagioclase. These occur as mineral clasts, both in the body of the brecciated meteorite and as inclusions in a variety of glassy materials, in rare microbreccia fragments, and also as the major minerals of holocrystalline lithic clasts of igneous appearance. The relative abundance of these glassy and lithic fragments varies from meteorite to meteorite. Microbreccia clasts are not volumetrically important except in Malvern, in which the largest fragment is of this type (see 3.2.1). Opaque minerals are distributed throughout the 'matrix' material of all five achondrites as separate clasts, and occur also as inclusions in other mineral clasts (particularly pyroxene) and in lithic and glassy fragments. Chromite and ilmenite are the main opaque phases present, and occur in all the achondrites examined. Troilite and Fe-Ni metal grains are more restricted in their distribution, but are locally abundant. Olivine and silica minerals are rare, and only traces of P-bearing phases could be detected by microprobe; none of these P minerals were positively identifiable by means of the microscope. Exotic components, e.g. chondritic materials, though searched for in all the sections studied, proved extremely rare and difficult to identify.

Petrographic descriptions of these components and of their modes

of occurrence follow. Wherever possible, reference is made to the photomicrographs set out in Plates 3.2 to 3.9 to illustrate and clarify these descriptions.

Pyroxenes

Most of the pyroxenes occur as sub-angular to subhedral mineral clasts that, together with plagioclases in a similar mode of occurrence, make up the bulk of the brecciated meteorites studied. A possible exception to this is Binda, in which a different style of brecciation has resulted in the presence of numerous large pyroxene-plagioclase fragments that may collectively make up a greater proportion of the meteorite than do the individual mineral clasts. Pyroxene fragments are the dominant inclusions in the glassy materials in all of the meteorites (e.g. Plate 3.3 B). This has a bearing on the mode of origin of these materials (see section 3.5). The lithic clasts in all five achondrites generally contain pyroxene associated with plagioclase in a variety of textures ranging from ophitic to granular (Plate 3.6).

The pyroxenes represented belong to both ortho- and clino- varieties in all the meteorites, but in widely varying proportions. In Binda, the bulk of the mineral is clear, colourless or with a faint brownish tint, and exhibits birefringence up to first order yellow. Zoning is absent. Its straight extinction, length-slow character, and large negative 2V confirm that it is an orthopyroxene. The clinopyroxene present occurs only as an exsolved phase in the orthopyroxene, and is easily recognized from its higher birefringence. Although the exsolution in this meteorite is characteristically coarser (Plate 3.8 C and D) than in the other meteorites, fine 'spindly' exsolution lamellae do occur in some of the orthopyroxenes (Plate 3.8 E). The optical characteristics of some of the wider exsolved lamellae and blebs indicate that they are augitic. In a number of pyroxenes,

exsolution of the Ca-rich phase has taken place along two distinct crystallographic directions. There is no marked difference that can be detected optically between individual pyroxene clasts and pyroxenes that occur in the numerous 'coarse-grained' lithic fragments in this meteorite (Plate 3.1 C; Plate 3.2 B, C, and D). The pyroxenes in Binda show evidence of shock; this is described in section 3.3.3.

The pyroxenes in Bununu occur mainly as angular to sub-angular clasts and tiny chips and splinters in the fine 'matrix' (Plates 3.1 D and 3.2 H). Orthopyroxenes and clinopyroxenes are present. Both varieties are, in general, clear and colourless, with little included material. Some clinopyroxenes have a faint brown coloration, while a few are crowded with tiny dark inclusions that impart a turbid appearance. The birefringence of both ortho- and clinopyroxenes is low; only a minority of the monoclinic variety shows second order colours. The orthopyroxenes have large negative $2V$'s, in contrast to the small positive angles of the pigeonite clinopyroxenes. Both types are unzoned and show exsolution, though less strikingly than the pyroxenes in Binda; the exsolved lamellae are much narrower than the Binda examples. The host phases are optically orthopyroxenes, while the higher birefringence of the exsolved material suggests a pyroxene richer in Ca. The exsolution takes several different forms. Some of the exsolution lamellae are very thin and sharply defined; those generally occur in orthopyroxenes with a very low content of Ca (Plate 3.8 A), and may be continuous or spindle-shaped. In some crystals wider lamellae are present, but discontinuous trains of irregular blebs are more common. As in Binda, the pyroxenes may exhibit two sets of exsolved bodies. These may be of similar type, e.g. both lamellar (Plate 3.8 G), or one set may be continuous and the other blebby (Plate 3.8 F).

Pyroxenes in Bununu occur also as inclusions in devitrified glassy

microbreccias (in which mode they are generally small, with the characteristics described above) and in lithic clasts, usually in association with plagioclase. However, lithic clasts are not abundant in Bununu. In most instances they are too small to give information on the texture of the rock from which they were derived, or that texture has been obliterated by cataclasis and subsequent recrystallization (Plate 3.2 G and H). The same result arises from the extremely shattered state of the components of most of the larger lithic fragments. Nevertheless, some of those clasts (invariably consisting of both pyroxene and plagioclase) appear to have had an original cumulate texture. No monomineralic aggregates of sufficient size to establish their original texture were seen. Small aggregates of pyroxene proved to be equilibrated assemblages of either orthopyroxene or pigeonite. Microprobe analysis subsequently revealed the variability of composition between several of the orthopyroxene aggregates, in sharp contrast to the very narrow compositional range present in diagenitic pyroxenes (e.g. FREDRIKSSON et al., 1976). Only three small lithic clasts with ophitic texture were observed. They are turbid because of a concentration of 'dusty' inclusions, and do not resemble any of the other constituents of the meteorite.

Most of the pyroxenes in Frankfort occur as sub-angular to subhedral clasts, with orthopyroxenes predominating over the monoclinic varieties, as might be expected from the magnesian character of this howardite. Despite the abundance of orthopyroxene, only three lithic clasts were observed in which this mineral occurs alone. All three show evidence of recrystallization. Two are fine-grained mosaic-like aggregates of turbid brownish crystals, and the third, which is of coarser grain, shows several 'triple junctions'. A further relatively coarse aggregate contains both ortho- and clinopyroxenes. Pyroxene-plagioclase clasts also are rare in Frankfort.

One such clast, with a sub-ophitic texture, is illustrated in Plate 3.6 A and B. It contains pigeonite with exsolved lamellae of ferroaugite. Another fragment observed consists of orthopyroxene and bytownite.

The pyroxenes in Malvern offer more variety, both compositionally and in their modes of occurrence, than those of the achondrites described above. The basic characteristics of the minerals are the same, but the proportion of clinopyroxene is markedly higher in Malvern than in the other three meteorites. Exsolution follows the pattern observed in Bununu and Frankfort rather than the coarser type exhibited by the Binda pyroxenes. As in Bununu and Frankfort, both varieties of pyroxene occur in a wide range of grain sizes as individual clasts in the body of the meteorite. In addition, they may be found as inclusions in glasses, glassy microbreccias, and the large microbreccia fragment depicted in Plate 3.1 A and G, both as individuals and as components of included lithic clasts.

Clinopyroxenes, ranging in size from about 200 microns to sub-microscopic dimensions, form the bulk of the matrix of the large microbreccia clast; plagioclase and opaque minerals make up the remainder. These clinopyroxene grains are sub-angular to sub-rounded, and their pale greenish-brown colour is darkened by abundant minute dark inclusions. The matrix pyroxenes and the larger included pyroxene clasts show extensive lamellar exsolution, and variation in their optical properties, e.g. the size of the optical axial angles, suggests that a wide range of compositions is present.

In the remainder of the meteorite, lithic clasts are more common and more varied in type than in Bununu and Frankfort. Direct comparison with Binda is more difficult because of the difference in brecciation. The largest lithic fragment in the Malvern sections examined exceeds 6 mm but, as noted earlier (section 3.2.1), far larger lithic clasts occur. Many of these clasts exhibit ophitic or sub-ophitic textures, but the granular nature of

others indicates that they have undergone recrystallization prior to incorporation in the howardite breccia. There is considerable variation also in the appearance of the lithic clasts. Many are composed of pyroxene and plagioclase that are clear and fully transparent, whereas other fragments, generally of ophitic texture, are so crowded with minute, dark, 'dusty' inclusions that they are difficult to distinguish from the surrounding 'matrix'. In a few clasts, pyroxene has been partially replaced by a concentration of small grains of troilite while the accompanying plagioclase laths have remained unaffected. In other clasts, the converse relationship was observed; clear pyroxenes are associated with plagioclases that are turbid because of partial replacement by a myriad of colourless, rod-shaped bodies oriented in two distinct directions. In some ophitic clasts, the pyroxene shows 'herringbone' twinning, which may indicate an augitic composition. Orthopyroxene in one sub-ophitic clast is associated with devitrified maskelynite (Plate 3.3 A; Plate 3.5 G and H) as described in a later section.

Lithic clasts with ophitic or sub-ophitic textures are in the majority, but a few show cumulate textures. The largest lithic fragment studied is of this type (Plate 3.3 D), and consists of orthopyroxene and plagioclase. No zonation of these minerals was detected, and the fragment appears to have been derived from an adcumulate, as defined by WAGER et al. (1960). Such clasts are rare in Malvern, and none were observed that contain only orthopyroxene. Several examples of clasts consisting of extremely fine-grained recrystallized mosaics of pyroxene, similar to those noted in Frankfort, occur.

The modes of occurrence of pyroxenes in Molteno are similar to those in Malvern, except that no comparable pyroxene-plagioclase microbreccia is present. Most of the pyroxenes occur as individual clasts in the 'matrix'

or enclosed in glassy materials, and are generally fairly small. The largest pyroxene clast observed measures just over 3 mm (Plate 3.1 H). The pyroxene fragments are angular to sub-angular, and comprise both orthorhombic and monoclinic varieties with the usual optical properties. As in the other meteorites, the mineral is unzoned in all its modes of occurrence. Fewer turbid and coloured clinopyroxenes are present than in Malvern. Exsolution has occurred, but is particularly evident in the clinopyroxenes, whether in the 'matrix' or the lithic clasts. The exsolved phase takes the form of very thin but regular lamellae in most occurrences. In general, exsolution is along a single crystallographic plane, but not invariably so. The coarser 'blebby' forms of exsolution are not common in Molteno.

Many of the lithic clasts in Molteno have suffered cataclastic breakdown to a greater or lesser degree. This has produced a granular texture in some pyroxenes, and local recrystallization of plagioclase. The original texture of some of these clasts can be seen to have been ophitic or sub-ophitic (Plate 3.6 E and F), but many clasts are too small to allow of any certainty on their texture, whether or not they have been cataclastically altered. The largest lithic clast studied (over 5 mm) has undergone severe cataclastic action (Plate 3.3 G), but can be seen to have been an orthopyroxene-plagioclase cumulate. The lithic fragments contain either ortho- or clinopyroxene in association with plagioclase, and no assemblages of orthopyroxene large enough to warrant identification as possible diagenetic cumulates were observed. One clast studied contains both orthopyroxene and pigeonite (Plate 3.6 G), but this is rare. This particular fragment may have undergone partial melting and recrystallization prior to incorporation in the meteorite breccia. The original texture may have been that of a cumulate with pigeonite as its main constituent, but parts of this rock appear to have recrystallized as large plates of plagioclase that poikilitically

enclose small granular pigeonites. The plagioclase crystals in these areas show a rough parallelism of optical orientation, and there is a corresponding alignment of some of the enclosed pigeonites. These features may indicate recrystallization while under moderate pressure.

Plagioclases

Plagioclase is the other main mineral constituent of the achondrites investigated. It is present in lesser amounts than pyroxene (Tables 3.1 and 3.2), but has similar modes of occurrence. The characteristics of the mineral are not identical in each of the meteorites. In general, however, crystal clasts in these meteorites do not in their habit resemble the plagioclases in lithic clasts of basaltic (eucritic) appearance, and may instead have originated from plagioclase-bearing cumulates.

In Binda, the plagioclases are generally clear, although some of the more extensively fractured crystals have zones of brownish 'dusty' inclusions bordering fractures. Larger inclusions present in other crystals proved to be troilite. The plagioclases are subhedral to euhedral, less angular than the pyroxenes in the meteorite. Rounding of plagioclases, both in the 'matrix' and at the margins of lithic fragments, has resulted from cataclastic action (see section 3.3.3). In some lithic clasts, the plagioclases display curved boundaries against each other and against the associated pyroxenes. The optical properties of the plagioclases, including their very high negative optic axial angles, are indicative of highly calcic compositions. No zoning was observed. Most crystals show polysynthetic twinning, which is very fine in places. Many of the plagioclases are twinned according to both Albite and Pericline laws (flat-stage determinations).

The lithic clasts in Binda are coarser-grained than those in the other four achondrites. The texture of the rock (or rocks) from which they were derived is therefore difficult to determine, but the arrangement of

pyroxenes and plagioclases in the lithic fragments suggests the possibility of a cumulate parent that may have had a layered structure (Plate 3.2 B, C, and D). No recrystallization of plagioclase to form fine-grained mosaics was noted in Binda, and devitrified plagioclase glass (maskelynite) also is absent.

The more highly brecciated howardite Bununu contains plagioclase mainly in the form of sub-angular to subhedral crystal clasts, most of which are completely free of inclusions. In addition to these clasts and similar fragments included in devitrified glasses and glassy microbreccias, finely-comminuted plagioclase is abundant in the 'matrix'. No zoning was noted. Polysynthetic twinning, apparently on the Albite law only, is common. The optical characteristics indicate a high-Ca form of the mineral. Plagioclase occurs in the scarce lithic fragments, which are possible cumulates, fine-grained recrystallized mosaics of pyroxene and plagioclase (Plate 3.2 H), or ophitic. No maskelynite was observed.

The proportion of plagioclase in Frankfort is smaller than in the other four meteorites, and the occurrence of the mineral is restricted virtually to individual clasts and comminuted material in the 'matrix' because of the rarity of lithic clasts and glassy materials. The plagioclases are generally polysynthetically twinned and are Ca-rich. The most common type of lithic clast has a sub-ophitic texture, with plagioclase laths projecting into larger crystals of pigeonite (Plate 3.6 A and B). No zonation was seen in any of the plagioclases.

The plagioclases in Malvern large enough for identification are sub-angular to subhedral and are mainly free of inclusions, although they are not as clear as those in Bununu. Some of the crystals, especially in lithic clasts, are crowded with tiny transparent rod-like bodies aligned in two crystallographic directions; these impart a turbid appearance to the mineral.

Plagioclase clasts occur as inclusions in all the glassy, and devitrified glassy, materials in the howardite. The mineral occurs also as lath-like crystals associated with pigeonite in ophitic clasts, which are moderately abundant, and in fine-grained recrystallized aggregates that in some instances contain pyroxene also. As noted in the section on pyroxenes, plagioclase is present in lithic clasts that display possible cumulate textures. One such clast, composed of plagioclase only, is included in the large microbreccia fragment (Plate 3.1 A and G) in which granular plagioclase is a major constituent of the 'matrix'.

Devitrified maskelynite is more common in Malvern than in the other four meteorites, and occurs in a variety of modes, e.g. as small clasts, as patches in recrystallized pyroxene mosaics, as rare inclusions in the large microbreccia fragment, and in association with orthopyroxene in a lithic clast (Plate 3.3 A and Plate 3.5 G and H). In this clast, reaction between the anorthitic glass and low-Ca pyroxene has produced a boundary zone with a very fine symplectitic texture, apparently an intergrowth of the two phases.

The plagioclases are high-Ca types and show no zonation. They are generally twinned on the Albite law only, but a few crystals, particularly those in clasts with possible cumulate textures, display twinning on both Albite and Pericline laws.

In Molteno, the plagioclases are similar to those in Malvern in their composition and modes of occurrence, but tend to be more angular and more turbid (because of oriented inclusions similar to those described earlier), and to show more evidence of recrystallization, especially in lithic clasts of possible cumulate origin. Clasts consisting of recrystallized mosaics of plagioclase, alone or with pyroxene, were noted. Some devitrified maskelynite also occurs, but is much rarer than in Malvern. The

plagioclases in lithic clasts with ophitic or sub-ophitic textures are generally fairly free of inclusions. None of the plagioclases are zoned. Twinning on one law only is general, even in fragments with cumulate texture.

Olivines

No olivines were found in Binda, Bununu, or Frankfort, and the mineral is of very minor importance in Malvern and Molteno. A few small angular clasts occur in the 'matrix' of Malvern, and one fragment is included in a glassy microbreccia clast. All the crystals are clear, pale greenish, and extensively fractured. They have high birefringence and very large negative optical axial angles, and show no zonation. The only olivines observed in Molteno occur, in contradiction of the observation of DESNOYERS and JÉROME (1973) that howarditic olivines occur only as isolated grains, in a single monomineralic aggregate about 1.7 mm long. They are clear, with a slight brownish tint, and contain small opaque inclusions. Some have round outlines and appear to be partially enclosed in larger plates, suggesting a cumulate origin. Some recrystallization has taken place in parts of the clast producing a fine-grained mosaic texture in which olivine is the only component. The crystals are unzoned, and have high negative 2V's as observed in Malvern.

Silica minerals

Silica minerals were found only in Binda, Frankfort, and Malvern, and are extremely rare (Table 1.2). The two examples observed in Binda occur in the same plagioclase crystal, where they partially replace two of the twin lamellae that have a common optical orientation (Plate 3.9 E and F). The mineral is transparent and colourless, with low birefringence and straight extinction. It contains randomly-orientated needles of a highly-birefringent mineral, presumably rutile. Its low refractive indices show it to be either tridymite or cristobalite, but a positive identification could not be made.

Two small clasts of a similar mineral were noted in the 'matrix' of Frankfort, and one in a similar situation in Malvern. The Malvern example is biaxial positive, indicating that it is tridymite. Its patchy extinction may have resulted from inversion from a high-temperature form of the mineral (MASON, 1972b).

Chromites

Chromite is present in all the meteorites examined. In Binda, the mineral occurs most commonly as small sub-angular clasts in the finer-grained material interstitial to the dominant coarse-grained components of the breccia. It is present also in the pyroxenes and, less commonly, the plagioclases of these coarse lithic fragments, where it is situated preferentially at grain boundaries or in fractures in the minerals. One chromite inclusion was noted in a fragment of devitrified glass. In this meteorite, the chromite is invariably black and opaque. Some of the grains have a thin rim of ilmenite.

The 'matrix' of Bununu contains many tiny chips of chromite, mostly too small for analysis, but larger clasts also occur. These are angular to sub-angular, and are generally black and opaque. However, some of the chromites are translucent and deep reddish-brown. A few inclusions of the mineral in pyroxenes were noted; none occur in the plagioclases, nor in the glassy components of the meteorite. Some intergrowth with ilmenite was observed, but the ilmenite rims seen on some of the Binda chromites are absent from this meteorite.

Chromite, the main non-silicate phase in Frankfort, is uniformly black and opaque. It occurs mainly as sub-angular clasts in the 'matrix'. One instance of its inclusion in a plagioclase clast was noted, but none was observed in the pyroxenes. The chromite clasts are generally small, but one has a maximum dimension of 2 mm. A few small fragments of intergrown

chromite and ilmenite are present in the 'matrix'.

Malvern contains black chromite, dominantly as small sub-angular clasts in the 'matrix'; the largest of these is 0.6 mm long. Rare chromite inclusions occur in the pyroxene or the plagioclase of a few coarse-grained lithic fragments. The mineral was not observed in any of the lighter-coloured, transparent glasses in the howardite, but it does occur in the dark brown glassy microbreccias, though in minor amounts. Intergrowth with ilmenite is again present, and at least one chromite clast was seen to be rimmed by ilmenite. Chromite is a constituent also of the large microbreccia fragment present in Malvern (Plate 3.1 A and G). Small grains of the mineral are distributed throughout the equigranular matrix of that lithological type, but there, as in the main meteorite breccia, chromite is subordinate in amount to ilmenite.

In Molteno, the main occurrence of chromite is as small sub-angular clasts scattered through the 'matrix', but a further important location for the mineral is in the glassy microbreccias, where included clasts up to 0.4 mm across were observed. Coarse-grained lithic clasts do not generally contain chromite as an accessory, but the mineral is included in one unusual clast (Plate 3.6 G) as intergrowths with ilmenite. Chromite-ilmenite intergrowths occur elsewhere in the meteorite, and in one place chromite appears to be associated with troilite.

Ilmenites

Ilmenite occurs in all five achondrites, but in very varied amounts. In Binda, it is relatively unimportant compared with chromite and troilite. It is generally associated with chromite, either as intergrowths or rims. In one small pyroxene, the mineral appears to fill a fracture. If this observation is correct, it supports the idea of a late origin, or re-mobilization, of the ilmenite that is suggested by its occurrence as rims on chromite grains.

Ilmenite is subordinate in amount to chromite in Bununu. Its main occurrence is in the 'matrix', and no large clasts are present. It was observed as an included mineral in both pyroxene and plagioclase, and also in the inclusion-packed matrix of a glassy microbreccia clast. Intergrowth with chromite occurs, but ilmenite does not form rims on chromite as in Binda. The ilmenite in Frankfort is also of minor importance, and has similar characteristics to that in Bununu.

In Malvern, ilmenite assumes greater importance and is more abundant than chromite. It occurs as clasts in the matrix, in which setting it may be intergrown with troilite. A single example of its occurrence as a rim on chromite was observed. Some clasts of the mineral are present in the matrix materials of glassy microbreccias, and a plagioclase aggregate enclosed in a large fragment of glassy microbreccia contains accessory ilmenite. The principal occurrence, however, is as an accessory in coarse-grained lithic clasts composed of pyroxene and plagioclase, particularly those of 'basaltic' appearance. In some of these, the ilmenite is associated with abundant, finely-disseminated troilite. Ilmenite is an important constituent of the large microbreccia fragment, in which it occurs as scattered clasts and as irregular aggregates of grains, and also as an accessory in lithic clasts included in the microbreccia. The largest ilmenite aggregate is surrounded by a broad zone of isotropic cryptocrystalline material that could not be identified.

In the matrix of Molteno, small clasts of ilmenite and chromite are approximately equally abundant; in places, the two minerals are intergrown, a relationship seen also in one unusual lithic clast (see the section on chromites). In general the modes of occurrence of the ilmenite are similar to those described for Malvern, with the mineral present additionally in clasts of devitrified glass and in a fine-grained granular lithic clast that appears to have been recrystallized.

Troilites

This sulphide is present in all five achondrites. It is less abundant than chromite in Binda, but has similar modes of occurrence to that mineral. It occurs both within the minerals of the lithic fragments, particularly the pyroxenes, and also along the boundaries between them. Troilite was not observed in the replacement relationship described below for the other meteorites studied.

Bununu contains little troilite, and the mineral was not observed as individual clasts in the 'matrix'. It occurs as disseminations of tiny inclusions in pyroxene crystals. This occurrence is interpreted as an early stage in the pseudomorphous replacement of pyroxene by troilite. A more advanced stage in this process may be visible in the form of 'spongy' masses of troilite, several of which were noted in the section. This replacement relationship is especially common in lithic clasts in which the minerals are turbid by reason of their high content of non-opaque inclusions.

Troilite is more abundant in Frankfort than in Bununu, but its mode of occurrence is similar. Disseminations of the mineral are present mainly in clasts that are aggregates of orthopyroxene, but partial replacement of at least one clinopyroxene was observed. 'Spongy' masses or networks of the sulphide are less common than in Bununu.

In Malvern, troilite occurs in similar disseminations and masses in the pyroxenes of coarse-grained lithic clasts, but these concentrations are larger and more widespread than those of Bununu and Frankfort. The mineral occurs also as discrete inclusions in plagioclase and in pyroxene, particularly orthopyroxene crystals. Rare instances of its occurrence in the matrix material of glassy microbreccia and in a devitrified glass were noted also. An association with ilmenite is evident in some of the turbid pyroxene-plagioclase clasts, and the two minerals appear to be intergrown in some

clasts in the 'matrix'. Their relationship suggests that the troilite is of later formation, but the evidence is not unequivocal.

The distribution of troilite in Molteno has some features not seen in the other four meteorites. Discrete clasts of the mineral occur in the 'matrix', and attain a maximum size of 0.2 mm. Some of these clasts appear to be intergrowths of troilite and metal. Furthermore, extremely fine-grained disseminations of troilite are present in the 'matrix'. The preferential replacement of pyroxene in lithic clasts noted previously was again seen in Molteno, but, in addition, individual clasts of pyroxene (mainly orthopyroxene) have been replaced by 'spongy' masses of sulphide. In some instances, the replacement process has been so complete that almost all traces of the original mineral have been obliterated. Discrete inclusions of troilite occur in the pyroxenes of lithic clasts, particularly those with cumulate textures, and a single instance of this type of occurrence was seen in the plagioclases of a possible plagioclase cumulate.

One thin section of Molteno contains a poorly-defined, dark isotropic mass shown by later analysis to be rich in SiO_2 and S. This material appears to be a highly siliceous glass, presumably of impact origin, that contains a dense concentration of troilite inclusions. The mode of formation of the sulphide is not apparent.

A further similar occurrence of troilite peculiar to Molteno was observed in one pyroxene-plagioclase clast. Parts of this clast appear to have been vitrified, possibly by impact, and these are crowded with minute angular grains of the sulphide that are, in places, so densely concentrated that it is not possible to determine the nature of the material in which they are included. This occurrence is interpreted as resulting from selective replacement, in varying degrees, of the glassy material in the fragment.

Metals

All the meteorites investigated contain very small amounts of NiFe metal. In Binda, however, only one small grain was observed. It is situated at a boundary between plagioclase and pyroxene in one of the lithic clasts, i.e. in the same type of occurrence as the troilite and chromite in the meteorite. The metal in Bununu is sparsely distributed through the 'matrix' in the form of tiny particles (maximum size about 150 microns). These metal grains are easily distinguishable in this occurrence (and in other types of occurrences in the other meteorites also) because they are surrounded by a 'halo' of oxide staining resulting from terrestrial weathering. One of the pyroxene clasts in the section of Bununu studied contains two inclusions of metal, but such inclusions are absent from the glassy materials in this achondrite. Frankfort also contains a minor amount of metal in its 'matrix'. Some of the grains have irregular margins, suggestive of infiltration of the 'matrix' material by the metal, and all are surrounded by rusty staining.

The content of metal in Malvern is greater than that of any of the three meteorites described above, but may be exceeded by that of Molteno. The metal occurs in the 'matrix' as small grains and as rare inclusions in orthopyroxenes in cumulate-type lithic clasts. It is most abundant, however, as inclusions in the glassy materials in this howardite. It was observed in all the types of glass present - in the clear glasses, in the dark brown matrix glass of the glassy microbreccias, and in the grey devitrified glasses and glassy microbreccias. Several small grains, and disseminations of grains, occur in the matrix of the large clast of coarse-grained microbreccia. In all of these occurrences, the metal is surrounded by a 'tell-tale' zone of staining. One instance of intergrowth of metal and chromite was observed.

Molteno's content of metal includes an irregular mass measuring 1.8 mm across. This large grain incorporates within its boundaries several

orthopyroxene crystals of moderate size (up to 0.3 mm) and 'matrix' material apparently identical to that in which the grain is situated. This feature, considered with the penetration (observed in the four polymict breccias studied) of 'matrix' material by metal, has implications for the origin and history of the metal that are discussed in section 3.5.5. Apart from the large grain, the modes of occurrence of metal in Molteno are similar to those in Malvern - in the 'matrix', in the various types of glassy materials, and included in pyroxenes that form part of lithic clasts. In one lithic clast, metal may be associated with finely-disseminated troilite, but in very minor amount.

Glassy materials

In all five achondrites, glassy material is present. Binda and Frankfort contain only minor amounts, but the various types of glassy materials that occur in Bununu, Malvern, and Molteno make up a substantial proportion of these meteorites (Tables 3.1 and 3.2). Microscopically, three major types can be distinguished:

- (a) 'True' glass - this variety exhibits characteristics generally associated with the glassy state: it is clear and transparent, and has arcuate fractures and smoothly curving boundaries that tend towards sphericity; it is isotropic, or shows only incipient devitrification in cross-polarized light; and it may occur interstitially to inclusions or to microlitic quench crystals resulting from partial devitrification.
- (b) Glassy microbreccia - this term is applied to the irregularly-shaped masses of dark glassy material that are particularly common in Malvern and Molteno, and that exhibit the following features: the glassy material of the matrix is generally very dark brown and almost opaque in plane-polarized light; this glassy matrix is crowded with included material that closely resembles the surrounding meteoritic breccia in

the size-range and variety of mineral and lithic clasts present; the irregular margins of the glassy microbreccias are, in places, vague and indistinct, and appear to merge with the adjacent 'matrix'; and only limited devitrification of the glassy matrix has taken place.

- (c) Devitrified glass - in this category are placed all glassy components that have been altered substantially by devitrification and now have the following characteristics: the former glassy matrix has been replaced by an extremely fine-grained, essentially crystalline, granular aggregate that is grey in colour and has a low birefringence; this aggregate generally contains inclusions of pyroxene, plagioclase, and opaque minerals, suggestive of an origin similar to that of the glassy microbreccias; these pyroxene and plagioclase inclusions are invariably turbid because of a high content of minute included (or exsolved) bodies; and all clasts of devitrified glassy material have regular boundaries that contrast sharply with those of the glassy microbreccias and indicate that the now-devitrified material was not formed in situ, but was introduced into the meteoritic breccias as an exotic component.

In practice, distinction between these three categories is not always easy because many gradational varieties exist. In addition, rare examples of other glassy materials that do not fit into this empirical three-fold 'classification' were encountered; these are mentioned in the appropriate descriptive sections below.

In Binda, glass and typical glassy microbreccia, as defined in (a) and (b) above, are absent, but clasts of an extensively devitrified glassy material containing many small inclusions of plagioclase, and subordinate inclusions of pyroxene and opaques, are distributed through a restricted area equivalent to about 30% of the section studied. These clasts are regular in outline and of a grey colour, and range in size from 200 microns to about

2 mm. The largest clast is featured in Plates 3.2 A and 3.5 B. They are most accurately classified as devitrified glasses, but were referred to as "glassy microbreccias" in the earlier stages of the present investigation, and these terms may be used interchangeably when these clasts are described or when data relating to them are plotted.

Bununu offers a greater variety and amount of glassy materials than Binda. 'True' glass is present in the form of one irregular mass, of which part only is preserved in the section studied, and a number of smaller clasts scattered through the 'matrix'. The irregular mass has a maximum dimension of 3.5 mm, and appears to have intruded the 'matrix' while in a molten state because it encloses pockets of 'matrix' material within it (Plates 3.1 D and 3.2 E). The glass is pale reddish-brown and is free of other inclusions. It is extensively fractured (Plate 3.4 C) but, as this feature is absent from all other glasses studied, the fracturing may have been produced during sectioning. The glass is not truly isotropic. Incipient devitrification has occurred at the margins of the mass, and the main body of the glass shows well developed spherulitic extinction, which is indicative of partial devitrification (Plate 3.4 D). The other glasses are similar in colour, but have more regular outlines and are characterized by the presence of small circular areas of finely-divided dark material with, in places, a dendritic structure. These dark spots are interpreted as centres of incipient devitrification, a conclusion reached also by BUNCH (1975), but the glasses in which they occur are completely isotropic (Plate 3.4 A). Some clasts contain inclusions of plagioclase and pyroxene, and, in one instance, spherules of metal. Some of the plagioclase inclusions appear to have been partially melted, but, in general, the pyroxenes are unaffected, even to the extent of retaining their original euhedral form in places.

The glassy microbreccias in Bununu are distributed throughout the

meteorite as sub-angular to sub-rounded clasts, the largest of which is about 5.8 mm across (Plate 3.2 G). They show extensive devitrification, and represent a transitional stage between categories (b) and (c) of the empirical classification of glassy materials used in this investigation. The larger clasts are a mixture of pale brown and grey material, the colour change being indicative of the degree of devitrification of the formerly glassy matrix. Inclusions of pyroxene, plagioclase, and ilmenite are present, but pyroxene is the most abundant (Plate 3.5 C). Some of the clasts have incorporated considerable amounts of 'matrix' material, in a few instances to the extent that it is difficult to discern the clast boundaries. One such clast contains a small, rounded inclusion of glassy microbreccia that presumably formed part of the incorporated 'matrix'. No metal grains were noted among the included material in any of the microbreccias.

Frankfort contains no glasses of category (a), but has representatives of both of the other categories, though sparse in number. One devitrified glassy microbreccia, with inclusions of (in order of importance) orthopyroxene, clinopyroxene, plagioclase, and chromite, is present, and measures about 1.5 mm across. All the other clasts are of the grey colour that signifies complete devitrification, have dimensions of only a few hundred microns, and mostly contain turbid, indistinct inclusions of pyroxene and plagioclase. Some clasts include euhedral laths of twinned plagioclase (Plate 3.5 D), in some places poikilitically enclosed in turbid clinopyroxene. The devitrified material in such clasts may originally have been the glassy mesostasis in extrusive 'basaltic' rocks.

JÉROME and CHRISTOPHE MICHEL-LÉVY (1971) drew attention to the abundance and variety of glassy materials in Malvern. All three categories, but particularly the glassy microbreccias, are well represented. The 'true' glasses are similar to those described for Bununu, but no large intrusive

masses comparable to that seen in Bununu occur in the Malvern sections studied. The glasses range in colour from very pale yellow to deep brownish-orange, and several clasts show distinct flow-banding, suggestive of deformation while in a plastic state (Plate 3.4 B). Some of the glasses occur as spherules or the fractured remnants of spherules that may have originated as droplets (Plate 3.4 F, G, and H). These spherical bodies are free of inclusions, but the other glassy clasts in Malvern contain sparse inclusions of pyroxene, plagioclase, ilmenite, and metal (Plate 3.4 B). In general, these included fragments are far fewer and very much smaller than those in the glassy microbreccias. Some glassy fragments are partly anisotropic as a result of shock or incipient devitrification, as revealed by the presence of crystallites in the birefringent areas. More extensive devitrification has taken place in other glassy fragments, with the production of euhedral microlites - possibly of orthopyroxene and minor clinopyroxene - that locally show well-developed parallel orientation. Most of these pyroxene microlites may have been formed by quench crystallization. Their parallelism may have resulted from limited flow while the glass was still plastic.

Differences in the time of formation of some of the 'true' glasses are indicated by their inter-relationships, and their relation to the glassy microbreccias. There are several instances of typical glassy microbreccias occurring as inclusions in typical, pale brown glass that gives the impression of having wrapped itself around the earlier-formed microbreccia. Conversely, there is clear evidence of the incorporation of reddish glassy material in certain of the glassy microbreccias, but these glasses differ in appearance from the most commonly-occurring type in Malvern and may be presumed to be of different origin. The reddish glasses therefore pre-date the formation of the typical glassy microbreccias, which in turn are of earlier

origin than at least some of the pale brown glasses with dark spots.

Irregularly-shaped masses of glassy microbreccia ranging in size from tens of microns to an observed maximum of 7.5 mm are widely distributed throughout Malvern (Plates 3.1 F and 3.3 A, B, and D). The boundaries of some of the smaller clasts, and parts of the margins of some larger masses, are indefinite and appear to merge into the 'matrix'. In places, the glassy material may be seen to have intruded, and partially enclosed, comminuted 'matrix' (cf. the large mass of glass in Bununu). Most of the larger microbreccia clasts are fractured, many having been broken into several pieces now separated by 'matrix'. Where no devitrification has taken place, the glassy material that has incorporated or welded together fragmental components similar to those present in the remainder of the meteorite is deep brown. With increasing devitrification, this colour pales and tends towards the grey of the cryptocrystalline, completely devitrified glasses. Many of the examples of this transition are present in Malvern. Sharp boundaries that exist within single clasts between materials of different colours may indicate inclusion of one glassy microbreccia in another, but this phenomenon is rare.

The glassy microbreccias in Malvern are noteworthy for their content of metal. Minor amounts of ilmenite and chromite are present, but metal is the most abundant opaque phase. It occurs as scattered grains with an average size of about 100 microns. Many of these grains have rims of finely disseminated metal and troilite interpreted as peripheral alteration by DESNOYERS and JÉROME (1977).

The devitrified glassy materials in Malvern are similar to those previously described, and occur in a wide range of clast sizes (Plate 3.3 D). These devitrified glasses do not occur as inclusions in other glassy materials, but are present in moderate amount in the large microbreccia fragment.

They are practically devoid of opaque inclusions, but rare metal grains, and even rarer troilites, were observed. Several examples of clasts composed of remnants of pyroxene and plagioclase in a matrix of devitrified material, similar to that described from Frankfort and presumably having a similar lithic origin, were noted and, in one instance, photographed (Plate 3.5 E).

Malvern contains a few glassy components that do not conform to the empirical classification used. The most interesting is an angular clast, 1.5 mm long, consisting of greyish-black glass in which are present large, randomly-orientated, stumpy skeletal crystals, whose centres are apparently also glassy (Plate 3.4 E). No other example of this lithological type was seen, but a single clast composed of similar dark glass devoid of crystals occurs in another part of the same section. Two glassy droplets of unusual appearance are illustrated and described in Plate 3.4 G and H. Quantitatively more important are the occurrences of maskelynite in the meteorite, described above in the section on plagioclase. These plagioclase glasses are invariably devitrified. The most important occurrence of this type of glass is illustrated in Plates 3.3 A and 3.5 G and H. Similar devitrified maskelynite has been reported from lunar breccias (e.g. JAMES, 1976, Fig. 17b).

The glassy materials in Molteno are difficult to classify because of the preponderance of transitional types present. 'True' glasses occur only as a few small clasts scattered through the fine 'matrix' of this meteorite. Glassy microbreccias with a dark brown isotropic matrix are also small and of rare occurrence; only one clast of moderate size (3.5 mm) was seen. Grey devitrified glasses likewise are present in minor amount (Plate 3.3 F). No glassy bodies of unusual appearance were noted, nor are there any possible glassy droplets. Classification is further complicated by the smallness of the pyroxene and plagioclase inclusions in the glassy materials, probably a consequence of the unusually fine-grained 'matrix' in this

howardite. In general, included material in the glasses is sparser and finer-grained than that in the glassy microbreccias in Bununu, Frankfort, and Malvern, but this is not true of Molteno. The most reliable criterion for classifying the moderately devitrified glassy materials in this particular howardite rests on the original colour of the glass. The material considered to have been originally 'true' glass, though now turbid because of the presence of crystallites, has retained its characteristic reddish-brown colour, whereas the glassy matrix of the microbreccias is darker brown and turbid, grading into paler shades of brown and grey-brown according to the degree of devitrification. This basis of subdivision appears to be confirmed by the other characteristics of the materials, e.g. evidence of flow is present in the reddish-brown clasts, but never in those considered to be glassy microbreccias, in agreement with observations from the other howardites. A typical glassy clast is illustrated in Plate 3.5 A, while glassy microbreccias appear in Plate 3.3 E and G. None of the glassy materials appear to be intrusive into the 'matrix'. All contain minor amounts of chromite, ilmenite, and metal. The glassy microbreccias have more included metal than the glasses, but considerably less than their counterparts in Malvern.

Unusual occurrences of glassy material in Molteno are the S-rich glasses described in the section on troilite, and the devitrified grey glass present in a few turbid lithic clasts. Similar clasts have been described from Frankfort and Malvern, but the Molteno examples suggest the invasion of pyroxene-plagioclase rocks by a glass that has subsequently devitrified. In one clast, for instance, pyroxene crystals appear to have been intruded and partly replaced by glass that has penetrated along cleavage planes.

Microbreccias

Microbreccia is an uncommon lithological type in the achondrites included in this investigation. Only one major example was observed, the large fragment in Malvern frequently referred to earlier in this chapter, and depicted in Plate 3.1 A and G. The matrix of the microbreccia is an equigranular aggregate of clinopyroxene and calcic plagioclase, with minor interstitial ilmenite, chromite, and metal (in order of abundance). Descriptions of these minerals have already been given. Inclusions of various kinds are present in the matrix - pyroxenes, plagioclases, fragments of grey devitrified glass, and lithic clasts. The devitrified glasses contain inclusions of pyroxene, plagioclase, and, in one instance, a small lithic clast. No other glassy components are present. The included lithic clasts comprise pyroxene-plagioclase rocks with ophitic texture, in which the pyroxenes contain many tiny oriented opaques and the feldspars are turbid, originally vitrophyric rocks with pyroxene phenocrysts set in a devitrified matrix, and a few very fine-grained recrystallized pyroxene-plagioclase rocks with mosaic texture.

Lithic clasts

All the meteorites studied contain lithic clasts, though in varying amounts. They consist essentially of pyroxene and plagioclase, generally together, and - very rarely - of olivine. The pyroxene may be orthopyroxene or pigeonite, but almost never both. Primary Ca-rich pyroxene is very rare, but secondary augite and ferroaugite are ubiquitous in the form of exsolved lamellae in Ca-poor pyroxene hosts. The plagioclase is invariably highly calcic. Ilmenite, chromite, troilite, and metal may be present in accessory amounts in the clasts. Full details of the occurrence of these phases in lithic clasts are set out in the appropriate sections above.

The lithic clasts exhibit a variety of textures, but two types

predominate - a sub-ophitic to ophitic texture, and a cumulate texture, the first being the more common. Fragments of ophitic character may be made up of pyroxenes and plagioclases that are clear and transparent, or turbid and cloudy because of included or exsolved material, as previously described, whereas the cumulate clasts are invariably clear. These cumulates generally consist of both pyroxene and plagioclase. Monomineralic aggregates, particularly of pyroxene, form at most only a small proportion of the lithic clasts present in any of the achondrites investigated, and most are too small for certainty that they were derived from pyroxene-only or plagioclase-only cumulates. Similarly, none of the cumulate fragments are large enough to indicate definitely whether banding or layering was present in the source rocks. Minor textural varieties consist mainly of rocks that have been partially or completely recrystallized. Complete recrystallization is generally indicated by mosaic texture, normally fine-grained and involving both pyroxene and plagioclase, but some fragments consist of extremely fine-grained mosaics of pyroxene with only very minor plagioclase. Fragments that exhibit two distinct types of texture, one of which is granular, are thought to have been partially recrystallized. Examples of the various textural types will be described briefly, with reference to relevant illustrations, at the appropriate places in the following summary of the occurrence of lithic clasts in each of the five achondrites.

As noted previously, lithic clasts form a major proportion of the constituents of Binda and their component minerals are similar in optical characteristics to the mineral clasts that make up the bulk of the meteorite. The lithic clasts are, unlike those of the other achondrites studied, of uniform textural type, apparently that of a cumulate. Ophitic and recrystallized textures were not observed. Reference has earlier been made to the coarsely brecciated character of Binda (Plate 3.1 C) and to its lesser

content of highly-comminuted 'matrix' relative to the other four achondrites. Previous observation of these features led to the view that Binda is a monomict breccia (DUKE, 1963). The bearing of the present investigation on this conclusion will be discussed after presentation of the data on the mineral chemistry of this unusual achondrite. The similarity of the lithic clasts to one another, and to the coarser mineral clasts, gives the impression of brecciation in situ, in which case the so-called 'lithic clasts' must be considered as fragments of the original pyroxene-plagioclase cumulate that have escaped complete disintegration (see Plate 3.2 B, C, and D).

Bununu contains the second-lowest proportion of lithic clasts observed in the five achondrites. Pyroxene-plagioclase aggregates of possible cumulate origin, recrystallized mosaics of pyroxene - alone or with minor plagioclase, and ophitic varieties are all present, but ophitic fragments are very rare. These lithic clasts are described in the section on pyroxenes, and are illustrated in Plates 3.2 F, G, and H, and 3.6 H. Selective replacement of the pyroxenes in some lithic clasts by troilite was noted. In one instance, the original texture of the clast may have been porphyritic (Plate 3.9 H).

Lithic clasts are rarest in Frankfort. They are generally too small for their textures to be established with certainty, but sub-ophitic varieties appear to be present (Plate 3.6 A and B). As previously noted, orthopyroxene aggregates are very rare in spite of the meteorite's richness in Mg. Some fine-grained recrystallized mosaics of pyroxene, or pyroxene and feldspar, were observed in this achondrite.

Malvern has a higher content of lithic fragments than either Frankfort or Bununu, and exhibits ophitic, cumulate, and recrystallized varieties. These have been adequately described in the preceding sections dealing with the pyroxenes and plagioclases in Malvern, and the various

types present are illustrated in Plates 3.3 A, C, and D, and 3.6 C.

Representatives of both ophitic and cumulate textures are included in the lithic clasts in Molteno, and a few that consist of fine-grained recrystallized pyroxene, or pyroxene and plagioclase, were noted also. Descriptions of the more important types of lithic clasts have been given in the sections on pyroxene and plagioclase, and are illustrated by Plates 3.1 H and 3.6 E and F. A feature worthy of note is the common occurrence in this meteorite of lithic fragments that have been partially or completely modified by cataclastic action and subsequent recrystallization, e.g. the cumulate clast depicted in Plate 3.3 G. The existence of two distinct textures in one lithic clast is tentatively considered to indicate partial melting and recrystallization of the source rock (Plate 3.6 G).

3.3.3 Shock effects

Shock effects are conspicuous in all the meteorites studied, as would be expected from their brecciated character. The severity of shock varies not only from meteorite to meteorite but also, in some instances, from clast to clast within a single meteorite, e.g. Bununu (see below). Previous mention has been made of the difference in style of brecciation between Binda and the other four achondrites. In Binda, both pyroxenes and plagioclases show patchy or undulatory extinction indicative of strain, and rare shock lamellae were noted in the feldspars (Plate 3.7 C). Both minerals are extensively fractured, but fracturing is more pronounced in the pyroxenes, probably because of their more brittle nature (Plate 3.2 A). Locally, mechanical deformation is severe in the plagioclases (Plate 3.2 C and D), but is generally evident in microfaulting and deformation of twin lamellae rather than complete shattering of the crystal (Plate 3.7 A, C, E, and F). Exsolution lamellae in pyroxenes show similar deformation. Some pyroxene-

plagioclase clasts convey the impression of having been shattered in situ. Other clasts show some effects of cataclastic action in the rounding of projecting corners, and local crushing is commonly seen in this meteorite where one clast impinges on, and partially penetrates, another (Plate 3.5 F; Plate 3.7 A, C, and E). These phenomena occur to this extent only in Binda. The 'matrix' of the meteorite is not so thoroughly comminuted as those of the other four achondrites (Plate 3.7 B). There is some evidence for slight post-lithification fracturing, e.g. the microfaulting of a small glassy fracture-filling in an orthopyroxene clast by later cross-fractures, some of which appear to extend beyond the clast (Plate 3.7 B).

Bununu exhibits the type of brecciation common to all the achondrites studied except Binda - shattered mineral and lithic components set in a 'matrix' of highly comminuted materials (see Plate 3.2 H) of similar character, as previously described. The clasts are generally fractured as in Binda, pyroxenes being more affected than plagioclases. Microfaulting of twin lamellae in plagioclase is present, but is less common than in Binda. Evidence of cataclastic action, of crushing, compression or shearing of clasts by their immediate neighbours such as was observed in Binda is absent. Most of the pyroxene and plagioclase clasts show abnormal extinction characteristics attributable to shock, but some appear to have remained unaffected. Closely adjacent materials of similar composition may show very different degrees of fracturing (Plate 3.2 F), and the normality of the optical characteristics of some plagioclase clasts suggests a total absence of shock effects (Plate 3.7 H). This anomalous situation was noted only in Bununu. The meteorite underwent very minor post-lithification fracturing.

Frankfort is a polymict breccia broadly similar to Bununu (Plate 3.1 E). All its components are extensively fractured and show abnormal extinction. Some clasts appear to have been impacted against one another,

but this feature is less common than in Binda. Fractures filled with a dark brown glass of possible impact origin occur in some clasts (Plate 3.7 D), and post-lithification movement is indicated by long similarly glass-filled fractures that traverse the 'matrix' of the meteorite. The degree of shock suffered by Frankfort appears more severe than that of Bununu.

All the compositionally diverse constituents of Malvern show fracturing and deformation, and those that are anisotropic have abnormal optical characteristics. These shock effects are similar to those described above. A rarer feature seen in Malvern is the development of shock lamellae in some plagioclase clasts (Plate 3.7 G). In situ disruption of bodies of glassy microbreccia was noted in this meteorite. Fracturing and separation of these fragile materials evidently took place prior to consolidation of the breccia; the interstices between disrupted sections of glassy microbreccia have been infiltrated and filled by comminuted 'matrix' material. Evidence of cataclasis present in some lithic clasts (zones of crushing, glass-filled fractures - see Plate 3.6 C and D) appears to relate to the source environment of these materials, not to the meteorite breccia in its present form, which contains no indications of cataclastic action. This observation applies equally to the occurrences of maskelynite in the achondrites investigated, and to clasts that have been thermally metamorphosed and recrystallized prior to incorporation in these meteorites. Poorly-defined fractures extending over distances of several millimetres in Malvern indicate a minor degree of post-consolidation movement.

The brecciation evident in Molteno is similar to that of Bununu, Frankfort, and Malvern (Plate 3.1 H), but the 'matrix' materials show a greater degree of crushing and comminution (Plate 3.3 F and H). The components of the meteorite show fracturing and shock features similar to those described from these three howardites. Evidence of limited cataclasis is

present in the form of a large pyroxene-plagioclase lithic clast that appears to have been crushed and broken through in situ (Plate 3.3 G). However, the lithic clast shown in Plate 3.6 E and F appears to have been cataclastically modified before its inclusion in Molteno. Some post-consolidation movement took place in the meteorite (Plate 3.3 H).

3.3.4 Chondritic component

All five achondrites were searched for a possible content of chondritic material, the presence of which is postulated by the physical mixing hypothesis for the origin of howardites advanced by JÉROME and GOLES (1971) and summarized in section 2.5. A review of work carried out on exotic inclusions in meteorites (WILKENING, 1977) shows that two gas-rich howardites, Jodzie and Kapoeta, contain a few fragments of carbonaceous chondrite material. This type of material is generally very dark and easy to distinguish, but none was detected in any of the five achondrites studied. A careful search failed to reveal any dark clasts that could not be assigned to one or other of the categories of glassy materials recognized in these meteorites (see section 3.3.2). This was confirmed by subsequent microprobe analysis. The search did, however, disclose the presence of a few unusual clasts that may be chondrules or parts of chondrules, and a description of these follows.

No material of possible chondritic origin was observed in either Binda or Bununu. Frankfort contains one example of what may be a rimmed chondrule (Plate 3.9 A and B). The anisotropic materials constituting the core and rim were not positively identified but appear to be identical and to consist mainly of Si, with minor amounts of Ca and Al. One fragment in Malvern, an aggregate of laths of brownish orthopyroxene that radiate from a common centre (Plate 3.9 C), is considered as part of a chondrule on the basis of its form and, possibly, its composition (see section 7.2.7). The

maximum dimension of this clast is only 1 mm. No other material in this howardite gives the impression of having originated from a chondrite; this includes the rare glassy spherules in the meteorite (Plate 3.4 F, G, and H). Molteno does not contain any definite chondritic component. The material that appears in Plate 3.3 F cannot reliably be considered as chondritic in origin.

The total number of possible chondritic fragments revealed by petrographic examination is therefore only two, and even their identification is very tentative. The possibility cannot, however, be precluded that chondritic material may be present in the 'matrix' in a form too finely-divided for detection by microscopic means.

3.4 MODAL ANALYSIS

Modal analysis was carried out on the sections of Binda, Bununu, Malvern, and Molteno using a 0.3 mm square grid. The results are set out in Tables 3.1 and 3.2. Bununu was counted twice, with the section in different orientations; the results of both counts, and their mean, appear in Table 3.1. For Malvern and Molteno, several sections were available (Table 1.1), and mean values, weighted to compensate for differences in the areas of the various sections, are presented. Counting was carried out on all six sections of Malvern (Table 3.2). Sections 1-4 are those used for microprobe analysis. Section 4 contains part of the large microbreccia clast described above. Allowance has therefore been made for the presence of two different lithologies in this section; modes were obtained first inclusive, then exclusive, of the microbreccia, and also for the clast itself, and these are set out in the table. Moreover, the modes derived from sections 5 and 6 are considered less reliable than those determined on the others because the thickness of these two sections impaired identification. Separate modes were

Table 3.1. Modal data on the achondrites Binda, Bununu, and Molteno (volume %)

CONSTITUENT	BINDA	B U N U N U			M O L T E N O				
		Traverse 1	Traverse 2	Mean	Section 1	Section 2	Section 3	Section 4	Weighted Mean
Plagioclase	27.85	15.42	13.59	14.51	14.46	12.70	15.47	14.79	13.97
Orthopyroxene	55.51	19.61	21.54	20.58	9.03	9.87	7.38	9.98	9.26
Clinopyroxene		22.06	24.75	23.41	34.77	36.67	38.66	42.51	37.07
Glassy microbreccia	---	0.96	1.07	1.02	4.94	5.16	8.08	2.22	5.10
Glass	---	4.00	3.56	3.78	0.63	1.45	0.18	0.74	0.90
'Matrix'	10.33	25.64	25.99	25.82	29.27	29.62	25.83	22.92	28.11
Opakes	4.33	6.28	4.57	5.43	4.30	3.33	3.34	3.70	3.72
Devitrified glass	1.85	6.04	4.93	5.49	2.61	1.01	1.05	3.14	1.85
Tridymite	0.13	---	---	---	---	---	---	---	---
Olivine	---	---	---	---	---	0.19	---	---	0.03
TOTAL	100.00	100.01	100.00	100.04	100.01	100.00	99.99	100.00	100.01
Points counted	1569	1673	1685		1418	1590	569	541	
Relative areas	---	---	---		2.6211	2.9390	1.0518	1.0000	

Table 3.2. Modal data on the howardite Malvern (volume %)

CONSTITUENT	Section 3			Section 4		Section 5		Section 6			Weighted means of sections		
	1	2		Incl. micro-breccia	Excl. micro-breccia	Micro-breccia					1-6	1-4 ^a	1-4 ^b 5-6
Plagioclase	16.31	14.33	14.22	10.74	18.19	20.77		8.16	13.37		12.66	13.68	15.71 10.86
Orthopyroxene	11.49	9.30	20.38	7.86	13.32	73.12		6.73	6.02		9.91	11.92	13.70 6.36
Clinopyroxene	16.16	15.94	10.76	8.27	14.02			10.88	19.52		13.46	12.39	14.24 15.35
Glassy microbreccia	25.00	32.83	21.28	10.74	18.19	0.0		58.64	32.19		29.78	21.17	24.32 44.94
Glass	3.66	3.04	2.38	1.82	3.08	0.0		0.82	2.53		2.31	2.66	3.06 1.71
'Matrix'	22.70	20.97	24.16	17.19	29.13	0.0		13.67	24.27		20.30	20.94	24.07 19.16
Opakes	2.23	2.85	1.64	0.82	1.39	4.98		0.75	1.33		1.51	1.78	2.03 1.05
Microbreccia	0.29	0.09	0.25	40.96	---	---		0.0	0.0		8.39	13.16	0.22 0.0
Devitrified glass	2.16	0.66	4.93	1.58	2.68	1.14		0.34	0.76		1.68	2.31	2.65 0.56
TOTAL	100.00	100.01	100.00	99.98	100.00	100.01		99.99	99.99		100.00	100.01	100.00 99.99
Points counted	1392	1054	1217	1704	1006	698		1470	1578				
Relative areas	1.3207	1.0000	1.1546	1.6167				1.3947	1.4972				

a - Including microbreccia; b - Excluding microbreccia

therefore calculated for sections 1-4 and 5-6, in addition to that determined for all six sections (Table 3.2).

Good agreement exists between the two determinations carried out on Bununu (Table 3.1). More variation is present in the Molteno analyses, but is attributable to the greater range of clast sizes present in comparison to Bununu (cf. Plate 3.1 D and H). This applies also to the modes of Malvern, in which the very irregular distribution of microbreccia is responsible for large differences between the various sections. The weighted means of sections 1-4 are considered the most accurate estimates of the modal composition of the howardite (Table 3.2). The first column represents the mode of the entire meteorite, including the microbreccia clast, while the second column provides an estimate of the mode of the normal lithology of Malvern, exclusive of the microbreccia.

An attempt was made to estimate the mineralogical compositions, in weight %, of the four achondrites for which volumetric modal data are available. Such estimates are necessarily rough for the following reasons:

(a) the specific gravities of the mineral phases must be estimated (DEER et al., 1966); (b) the relative proportions of pyroxene and plagioclase in the 'matrix' were assumed to be the same as in the remainder of the meteorite, and the highly probable presence of glassy and opaque materials was neglected; and (c) glassy constituents were assumed, from the petrographic evidence (see the following DISCUSSION) to have been formed in situ and therefore to contain the proportions of pyroxene and plagioclase characteristic of the host meteorite. The chemical evidence does not fully support this assumption, but the discrepancy is small and difficult to quantify, and is not taken into account. The figures in Table 3.3 therefore represent attempted reconstructions of the mineralogical compositions of the meteorite breccias prior to the formation of their glassy components.

Table 3.3. Rough estimates of the original mineralogical compositions (weight %) of four of the achondrites studied, based on the data of Tables 3.1 and 3.2 (for explanation, see text)

CONSTITUENT	BINDA	BUNUNU	MALVERN	MOLTENO
Plagioclase	27.2	19.5	30.5	18.8
Pyroxene	66.0	69.7	64.8	73.7
(Orthopyroxene)		32.6	31.8	14.7
(Clinopyroxene)		37.1	33.0	59.0
Opaques	6.7	10.8	4.7	7.5
(Chromite)	3.5	6.2	2.7	4.2
(Ilmenite)	3.2	4.6	2.0	3.3
Tridymite	0.1	--	--	--
TOTAL	100.0	100.0	100.0	100.0

3.5 DISCUSSION

In this section, an attempt will be made to assess the significance of the petrographic observations recorded above, and to relate them to recent published work in the same field. Much useful information exists in the literature, but in a very scattered form.

3.5.1 General petrography

The preceding accounts of the mineralogical and petrographic characteristics of the achondrites studied lend support to ideas that have been formulated in recent times to explain the formation of differentiated and brecciated stony meteorites. These ideas have drawn heavily on recently-acquired knowledge of physical processes operating at or near the surfaces of Earth's nearer neighbours in the inner solar system, notably the Moon. However, before the availability of direct evidence of these processes in the form of returned lunar samples and photographs, speculative

suggestions had been advanced on the part played by collisional impacts of heavenly bodies, both large and small, in the formation of brecciated meteorites. DUKE (1963) and DUKE and SILVER (1967) proposed that the brecciation present in almost all the basaltic achondrites and mesosiderites had resulted from meteorite impact on the surface of the parent body (or bodies). They attributed the presence of glassy materials, mainly maskelynite, to impact metamorphism on the basis of studies of the shock effects associated with terrestrial meteorite craters (CHAO, 1967; BUNCH et al., 1967).

The picture that has emerged from the present petrographic study of a more restricted range of achondrites than that covered by Duke and Silver is in broad agreement with the conclusions of these authors. Four of the meteorites studied have characteristics similar to the compound breccias recovered from the lunar highlands, but appear to have had a less complex formational history. None contain evidence of four generations of breccia, as reported from the lunar samples (e.g. TAYLOR, 1975); the maximum observed is three (in Malvern only). These meteorites may be inferred, by analogy with lunar breccias, to have been derived from a rubbly deposit built up, on the surface of their parent body, of successive layers of ejecta from meteorite impact craters. This regolith deposit was mixed and modified by later impacts. The lithological compositions of these four polymict breccias show that rocks made up of pyroxene and plagioclase, singly or in association, dominated the source areas. The fifth meteorite, Binda, does not resemble a lunar breccia. It is not essentially a compound breccia, although it contains about 2% of devitrified glassy microbreccia (Table 3.1). The appearance of this achondrite in thin section suggests that it represents a pyroxene-plagioclase cumulate that has been reduced to rubble in situ, and that the minor component of glassy material is a later exotic addition. The

petrographic investigation therefore supports the established view (DUKE and SILVER, 1967) that Binda is a monomict breccia. This conclusion is discussed later in the light of data to be presented on the bulk chemical composition and mineral chemistry of this meteorite.

Binda

There are few petrographic descriptions of Binda in the literature with which the account in this chapter can be compared. The original description (ANDERSON and MINGAYE, 1913) alludes briefly to anorthite, hypersthene, chromite, and specks of metal as the identifiable constituents. DUKE (1963) noted that the meteorite is composed of lithic clasts and tabular crystals of hypersthene and plagioclase that had suffered extreme mechanical deformation. He likened the sample studied to a gabbroic rock that now represents a tectonic, not an accumulation, breccia. The present study confirms this conclusion on the different type of brecciation seen in Binda, but the composition is not gabbroic and, as indicated by DUKE and SILVER (1967), the fragmentation of the meteorite has most probably been caused by meteorite impact rather than tectonic or volcanic agencies. DUKE (1963) records also the presence of dark grey cryptocrystalline material with birefringent inclusions. This presumably corresponds to the devitrified glassy microbreccia clasts reported in this investigation (Plate 3.2 A). The modal abundance of plagioclase (25%) recorded by DUKE and SILVER (1967) is in good agreement with that of Table 3.1. The observation of JÉROME (1970) that the content of troilite in Binda is above average for the achondrites included in his study provides partial support for the high percentage of opaque minerals in the mode (Table 3.1). MASON (1974) commented on the cataclastic brecciation of the meteorite and the deformation of the plagioclase noted also in the present study.

The petrographic differences between Binda and the other four meteorites, which are accepted as howardites, give rise to the question of

the classification of Binda, a topic that will be discussed elsewhere in this dissertation. The meteorite was classified as a howardite on the basis of its bulk composition (MASON, 1962; HEY, 1966; and HUTCHISON et al., 1977), which is Mg-rich (ANDERSON and MINGAYE, 1913; McCARTHY et al., 1973). A proposal (SHIMIZU and ALLÈGRE, 1975) that "Binda can be interpreted as representing solid equilibrated with eucritic liquid" finds neither petrographic nor compositional support from the present study; no evidence of eucritic components, nor of zonation of minerals that might indicate reaction with intercumulus liquid of eucritic composition, was observed. STOLPER (1975) tentatively suggested that Binda might be a cumulate eucrite directly derived from a eucritic melt. This suggestion was later (STOLPER, 1977a, 1977b) modified to derivation by fractionation of magnesian melts residual from the partial melting of the source materials that had produced the eucrites. This 'classification', which was based mainly on the cumulate texture of the meteorite and the fact that Binda does not plot with eucrites such as Juvinas and Sioux County on the 'pseudo-liquidus' projections used by STOLPER (1977a, Figs 5 and 6) to display his results, has unfortunately been adopted by other writers. TAKEDA and ISHII (1975) concluded that Binda had crystallized from a magma and did not owe its formation to the admixture of eucritic and diogenitic materials. They stated that Binda is "the most Mg-rich and Ca-poor eucrite", and subsequent work on lunar and achondritic pyroxenes by the Takeda group has assumed the validity of this classification (e.g. TAKEDA et al., 1976, 1979; TAKEDA, 1979). This assumption is made also by GARCIA and PRINZ (1978) in a brief petrographic description of the meteorite. As will be shown below, the present writer holds a different view of the classification of this important non-chondritic meteorite.

Bununu

No such classificatory doubt surrounds Bununu; it is generally accepted as a howardite (HEY, 1966). A brief petrographic description of the meteorite appears in MASON (1967). This is in general agreement with the observations recorded in the present work and, although other aspects of the meteorite's composition have been reported in the literature, appears to be the only available petrographic information. No mention was made of the occurrence of glass in the howardites.

Frankfort

DUKE (1963) supplied a brief petrographic description of Frankfort. In it he noted the scarcity of lithic clasts and the preponderance of orthopyroxene over pigeonite, and observed that all original textures had been obliterated by brecciation. MASON and WIIK (1966b) estimated the relative proportions of the ortho- and clino- varieties of pyroxene to be about 3:1, and noted the wide range of compositions displayed by the orthopyroxenes. Their examination revealed some tridymite, but did not find the olivine tentatively identified by BRUSH (1869). However, the mode supplied by DUKE and SILVER (1967) includes 1% olivine described as magnesian. This mineral was not found in the present investigation of the meteorite. In other respects, there is agreement with the published data.

Malvern

The first brief petrographic description of Malvern was given by JÉROME (1971), and was amplified by JÉROME and CHRISTOPHE MICHEL-LÉVY (1971). They recognised its polymict character and its resemblance to lunar breccias caused by the wide variety of lithic and glassy materials present. They also speculated on the presence of chondrules and volcanic material in the breccia, which they concluded was of impact origin. A further publication (DESNOYERS and JÉROME, 1975) continued to base description of the petrography on a

division into a dark lithology - the impact glasses here referred to as glassy microbreccias - and a light lithology corresponding to the 'matrix' and its included mineral and lithic clasts. These authors described the large enclave, termed 'microbreccia' in the present study (Plates 3.1 A and G), as a monomict breccia with the mineralogical characteristics of a eucrite. In the full presentation of their data (DESNOYERS and JÉROME, 1977), the enclave is described as a third lithology - a breccia within a breccia - and is referred to as a 'xenolith'. There is general agreement between the petrographic descriptions in their paper and in this dissertation, although some of their accounts tend to be over-simplified and lacking in detail. The present study does not confirm the following observations made in the paper: bimodality in the distribution of grain sizes in both light lithology and 'xenolith'; the scarcity of chromite and metal in the 'matrix'; and the absence of glassy material in the 'xenolith'. As noted above, it also does not confirm the implied lack of lithic clasts in the 'xenolith'.

No further comprehensive treatments of the petrography of Malvern have been published to date, but several recent papers (HEWINS and KLEIN, 1978; HEWINS, 1979a; MITTLEFEHLDT, 1979b) have provided specialized data on some of the components of the howardite. These will be considered in later sections.

Molteno

Only one account of the petrography of Molteno appears in the literature (FROST, 1971). The description is brief, but notes the brecciated nature of the howardite and the effects of strain in both pyroxene and plagioclase. The glassy material present was not recognized as such, but was proved by X-ray powder photography to contain pyroxene and plagioclase, and Frost suggested that the material had been mobilized by shock because it appears to have intruded coarser-grained parts of the meteorite. The

textures of some lithic clasts were described, and a very minor amount of olivine was reported. A high proportion of the opaques consist of troilite, some of which occurs in myrmekitic intergrowths with pyroxene that presumably correspond to the replacements observed in the present investigation. The modal analysis presented cannot be compared with that of Table 3.1 as, by Frost's admission, it must have been performed on unrepresentative material.

Other howardites

The petrographic characteristics noted in Bununu, Frankfort, Malvern, and Molteno in the present study have been described from other howardites. The conclusion of FREDRIKSSON and KEIL (1963) that Kapoeta is a monomict shock breccia because of the identity of chemical composition of its light and dark portions is no longer accepted. A more recent study of the components of Kapoeta, with emphasis on four isotopically-dated lithic clasts, clearly established its polymict character (DYMEK et al., 1976). These authors compared the howardite to the lunar breccias and inferred that it evolved, in conditions broadly similar to the lunar analogue, in an impact-derived regolith. They recognized two major lithologies in the lithic fragments. These they termed 'basaltic' and 'pyroxenitic', but stressed that these categories represent a compositional continuum, not two distinct source compositions. The division between the two broad types was set at $Fe/Fe + Mg = 0.4$ in the pyroxenes. Pyroxene-plagioclase ('basaltic') clasts show both volcanic and granular recrystallized textures. 'Pyroxenitic' components are rarer, with textures suggesting a cumulate origin. They are devoid of plagioclase, but may contain both ortho- and clinopyroxene. Dymek and his colleagues noted that lithic clasts make up only about 10% of the meteorite. The bulk consists of pyroxene and plagioclase clasts with a wide range of compositions. A very minor content of olivine was reported. Also present are several fragments of 'vitric breccia', which contains mineral and

lithic inclusions and appears to correspond to the glassy microbreccia clasts reported from other howardites in the present investigation. These 'vitric breccias' were regarded, as in the present study, as evidence of impact-melting in the regolith from which Kapoeta was derived. Dymek and his co-authors observed also that the absence of anorthositic clasts indicates that plagioclase fractionation played little or no part in the evolution of Kapoeta's source materials. This is in agreement with the observed lack of fragments of definite anorthosite in Bununu, Frankfort, Malvern, and Molteno, and will be discussed when the genesis of howardites is considered. The data on Kapoeta indicate its general similarity to these howardites, but Kapoeta has a definite chondritic component (WILKENING, 1973) whose presence was confirmed by Dymek and his fellow workers.

JÉROME and CHRISTOPHE MICHEL-LÉVY (1972) provided petrographic data on Washougal, which they described as "a very heterogeneous polymict breccia" and which appears to be composed essentially of mineral and lithic clasts similar to those found in other howardites, with one notable exception - a dunite fragment over 1 cm across (cf. the much smaller aggregate of olivine reported from Molteno in this work). Many pyroxenes in Washougal contain minute inclusions of troilite for which, as in the present study, a replacement origin was suggested. The authors drew attention also to the close juxtaposition of shocked and unshocked plagioclases of similar composition in Washougal, a phenomenon recorded in Bununu (see section 3.3.3 and Plate 3.2 F). Tridymite appears to be of more common occurrence in Washougal than in any of the achondrites included in this investigation.

One of the most comprehensive treatments of the petrography of howardites yet presented is that of BUNCH (1975), who attempted to classify the various lithic and glassy components found in these meteorites and to assign them to possible types of source rock - a procedure analogous to that

followed in the study of lunar breccias. The investigation included microprobe analyses of these components, and these compositional data are relevant to the part of the present study that deals with the phase chemistry of the five achondrites (Chaps 6 and 7). Of the 11 "howardites" studied by Bunch, two (Nobleborough and Pasamonte) are conventionally regarded as eucrites (HEY, 1966; HUTCHISON et al., 1977), although Nobleborough's polymict nature was recognized by MASON et al. (1979). The others are: Bholgati, Bununu, Frankfort, Kapoeta, Malvern, Pavlovka, Petersburg, Washougal, and Yurtuk. Comprehensive petrographic descriptions of individual meteorites are not given, but general conclusions are expressed on the basis of the study of all. Of these conclusions, the most significant to the present investigation is Bunch's agreement with other workers (SIMPSON, 1974, 1975; DYMEK et al., 1976) that howardites are not simple mixtures of eucrites and diogenites, but are made up of a variety of magmatic differentiates and related glassy, brecciated, and meta-igneous materials. Some of these bear a general resemblance to materials involved in the formation of lunar surface breccias, but others have neither lunar nor terrestrial analogues. Some of the lithic clasts distinguished by Bunch, notably his 'mafic' group (orthopyroxene rocks with minor anorthite), do not represent known meteorite types. From his petrographic and compositional data, Bunch concluded that the howardite parent body had undergone widespread differentiation in order to produce the major plutonic and extrusive igneous rock types that contributed lithic clasts to the howardites through incorporation and mixing in surface regolith breccias.

Several of Bunch's observations require comment. He distinguished a category of lithic clasts composed mainly of plagioclase ("Al-rich rocks") that he likened to the plagioclase-rich cumulate eucrite Serra de Magé (SCHNETZLER and PHILPOTTS, 1969; DUKE, 1969), and suggested that the larger

plagioclase clasts in howardites may have originated from such cumulates because they are of different habit from plagioclases that occur in the ophitic or sub-ophitic textures common to the majority of eucrites. As noted above (section 3.3.2), the petrographic observations made on plagioclase clasts in the present investigation are in complete accord with this suggestion. This implies, therefore, although Bunch did not state it, that a substantial amount of the eucritic material in the regolith deposits from which howardites were derived was of cumulate origin, i.e. similar to Serra de Magé, Moore County, or Moama, the only three examples of cumulates at present recognized among the eucrites, rather than the more common 'basaltic' types such as Juvinas and Sioux County. This will be considered again after presentation of the microprobe data from the current investigation.

Another of the observations in Bunch's paper that is in agreement with the present petrographic study concerns the rarity of diogenite clasts. Two only are recorded from his study - one in Bununu, the other in Bholgati. This is difficult to understand, particularly for Mg-rich howardites such as Frankfort and Bununu, if one is to believe that diogenites were major contributors to the regolith breccia from which howardites were formed, as required by the mixing hypothesis of JÉROME and GOLES (1971). Bunch attempts to explain this anomaly by stating (p. 481): "The contribution of hypersthene achondrite component to the howardites is probably large (the italics are mine) in view of the large amount of bronzite mineral clasts present in all samples." He does not, unfortunately, compare the compositions of these bronzite clasts with those of diogenitic orthopyroxenes, which have been shown to be very restricted (MASON, 1968; GOOLEY, 1972). Moreover, the diogenite clasts described by Bunch are granoblastic, and their pyroxenes accordingly bear no morphological resemblance to the orthopyroxene clasts abundantly present in all howardites. This topic will be returned to in a

later section (3.5.3), with particular reference to recent meteorite discoveries in the Antarctic.

Bunch noted that the boundary relationship between the large fine-grained microbreccia clast in Malvern and the main body of the meteorite indicates that "a sliding motion" had taken place (p. 473). No evidence for this conclusion was seen in the sections examined in the present investigation, but such movement would not be inconsistent with the minor, post-lithification fracturing that was observed (see section 3.3.1).

Bunch points out at the start of his paper that the rock names given to lithic lasts in the howardites are merely descriptive, not genetic, but his use of the term 'microgabbro' raises an important point and cannot go unchallenged. Reference to the petrographic data in section 3.3.2 will show that the five achondrites studied are virtually devoid of primary Ca-rich clinopyroxenes. On this basis, therefore, the clasts concerned should be termed 'micronorites' if it is absolutely necessary to assign a terrestrial rock name to them (STRECKEISEN, 1973). The plagioclases are, however, too calcic for strict application of the term.

The same author provides additional information on unusual lithic clasts in the Jodzie howardite (BUNCH et al., 1976). These are termed cumulate ferrogabbros by Bunch, and may resemble the large cumulate clast described from Malvern (section 3.3.2; Plate 3.3 D) in which, however, the orthopyroxenes are considerably more magnesian than those reported by Bunch. A more closely comparable lithic clast may be that in Molteno depicted in Plate 3.3 G. It is a cumulate with pyroxenes richer in Fe than the Malvern example (Fs_{40}) but which cannot be classed as ferrohypersthene, as in the Jodzie clasts. The Jodzie "gabbroic" fragments are considerably larger and coarser-grained than those in Malvern and Molteno.

A careful literature search covering the period between the publication of Bunch's data and the time of writing failed to uncover further general petrographic information except the observation of a single diogenite clast in Chaves (MASON et al., 1979), but specific features of the meteorites under consideration are discussed by a number of authors of papers published during the last seven years - a very active period of research on the achondrites. The following sections consider the new information and try to relate it to the observations of the present investigation.

3.5.2 Glassy materials

JÉROME (1971) and JÉROME and CHRISTOPHE MICHEL-LÉVY (1971) were the first to remark on the presence of abundant glassy material in a howardite (Malvern), and their observation was followed by the discovery (BROWNLIE and RAJAN, 1973) of glassy spherules in Kapoeta that have approximately the same composition as the bulk meteorite except for lower Na. More substantial amounts of glass were reported from Bununu by DESNOYERS and JÉROME (1974), JÉROME and DESNOYERS (1974), NOONAN (1974), NOONAN et al. (1974), and RAJAN et al. (1974), some of whom also provided additional information on the Malvern and Kapoeta glassy materials. All of these reports were of a preliminary nature, as were the observations of SIMPSON (1974, 1975). From them there emerges a picture of the varying amounts and morphologies of the glassy materials in these three howardites, together with recognition that their presence is indicative of the effects of shock on the regolith deposits from which the meteorites were derived. NOONAN (1974) described the glasses in Bununu and Malvern as "quenched, impact-melted rocks", while RAJAN et al. (1974) regarded the Bununu materials as similar to the 'agglutinates' found in lunar breccias, even to the extent of containing vesicles. This view is partially supported by the work of HEIKEN (1975) on the characteristics of

lunar 'agglutinates'. There may be a correspondence between the materials termed 'glassy microbreccias' in the present study and fine-grained 'agglutinates', which are formed in or near impact craters, where good mixing of regolith components is possible. The coarse-grained lunar varieties have clasts only on their surfaces, and their interiors are wholly glassy. If these have meteoritic counterparts, they are not easily identifiable. The estimate made by Rajan and his associates of the amount of 'agglutinate' present (0.1%) is considerably at variance with the mean modal amount of glassy materials (10.29%) determined in the present investigation (Table 3.1). The Jérôme group noted that the colours of various glasses in Bununu and Malvern gave no indication of composition, which proved generally similar to that of the bulk meteorite. They observed also the presence of mineral and metal inclusions in the glassy materials, and claimed that the large microbreccia 'xenolith' in Malvern is devoid of glass. The present study has, however, established the presence of a variety of included materials, including fragments of grey devitrified glass, in this microbreccia (section 3.3.2).

The paper by BUNCH (1975) made a more substantial contribution to knowledge on the glassy materials in howardites, although the petrographic descriptions are very brief. He noted that "both Malvern and Bununu contain lunar-like agglutinates" (p. 473), but unfortunately does not relate this observation to his own classification. Bunch subdivided the glassy materials into two main categories, glasses and impact melt rocks, that correspond roughly to the 'true' glasses and glassy microbreccias respectively of this work and SIMPSON (1975). In the howardites studied by Bunch, only Bununu and Malvern were noted to contain abundant glasses, which he defined as spheroidal or irregular bodies that may be absolutely "clean" (i.e. without inclusions or devitrification) or may show varying degrees of devitrification

and content of included material. Bunch observed that many of the glasses may have been hot when incorporated into the meteorite breccia because they are irregularly shaped and have been penetrated by matrix materials. He distinguished also three categories of melt rocks, only one of which (his Type IIIB) can be directly related to the glassy microbreccias observed in the present study. Bunch described clasts of this type as containing "rounded, partly melted minerals in a glassy brown cryptocrystalline matrix". The colour and degree of crystallinity of the matrix would, in the present investigation, be interpreted as indicative of only incipient devitrification of glassy microbreccia, and therefore not worthy of separate classification. Bunch's Type IIIC melt rocks would probably be regarded as devitrified glasses by this writer, while his Type IIIA, which he described as rare and virtually restricted to Malvern, appears to correspond to the glass with quench crystals that was observed in that meteorite. The major glassy component in Bununu was described by Bunch as having an "intrusive" relationship with the other brecciated materials. He classified this "intrusive" melt rock as Type IIIC (i.e. having a "basaltic" matrix). By contrast, only marginal devitrification is present in the large intrusive glassy body in the section examined in the present investigation (cf. Plates 3.1 D, 3.2 E, and 3.4 C of this report with Bunch's Figs 1 c and 6 b). They are evidently different bodies. Confirmation of this may be found in KLEIN and HEWINS (1979).

DYMEK et al. (1976) described fragments of 'vitric breccia' that occur in Kapoeta in addition to the glassy clasts noted by BROWNLEE and RAJAN (1973), to which they are compositionally similar. The matrix material of these breccias is dense, dark brown, and is composed of "very fine-grained mineral debris and (devitrified) glass" (p. 1124). These 'vitric breccias' appear to correspond to the glassy microbreccias present in the meteorites

described in this chapter both in the characteristics of the matrix and in the nature of the included clasts. They were interpreted by Dymek and his colleagues as "shocked, melted, and lithified regolith". The abundance of these breccias in Kapoeta was not indicated, but they are presumably fairly rare.

The high proportion of glass in Malvern was commented on by DESNOYERS and JÉROME (1975, 1977); their estimate of about 20% is exceeded by the modal value determined in the present study (Table 3.2). They made no subdivision of the glassy components of the meteorite, but recognized the presence of inclusions of pyroxene and plagioclase in some clasts, and the differing extent to which devitrification had proceeded in the glasses. They noted also that almost the entire content of metal in Malvern occurs in the glasses. Rare grains of olivine and chlorapatite were reported as inclusions also, signifying that the fragmental materials from which the glass had been formed had contained some olivine. The present study did not observe any olivine in this mode of occurrence.

HEWINS and KLEIN (1978) produced the most detailed study of the melt rocks in Malvern to date. Their petrographic data were supplemented by experimental work on the crystallization kinetics of the various types of glassy materials they distinguished - brown glass, brown glass with orthopyroxene 'dendrites', and dark matrix breccia. The last-named clearly corresponds to the glassy microbreccias of this investigation. Hewins and Klein showed that the matrix material of the examples of this type that they studied was crowded with so-called dendrites of orthopyroxene compositionally slightly more Fe-rich than those in the brown glass. This observation suggested that the pyroxenes in the dark matrix breccia had crystallized at lower temperatures than their equivalents in the glasses, probably because of rapid cooling caused by the incorporation of numerous clasts of pyroxene

and plagioclase in the one melt but not in the other. The experimental results indicated that the beads and spherules of brown glass devoid of pyroxene crystallites probably cooled in flight at rates greater than $10^{\circ}\text{C}/\text{min.}$, and that the melt rocks containing pyroxenes cooled at rates less than that value. The data confirmed that local undercooling of these melt rocks caused by cold inclusions produced the highly crystalline dark matrix breccia. The phenomenon of nucleation of orthopyroxene crystallites at the interface between brown glass and an included clast reported by Hewins and Klein was not observed in the present study.

The same authors investigated the impact melt rocks in Bununu also (KLEIN and HEWINS, 1979), concentrating on the intrusive body observed by BUNCH (1975), and drawing comparisons between the glassy materials in Bununu and Malvern. Their experimental work showed that the cooling rate required to produce glass with the composition of that in Bununu is only about $0.3^{\circ}\text{C}/\text{min.}$ - thirty times lower than the value determined for Malvern (HEWINS and KLEIN, 1978), despite the general chemical similarity of the glasses in the two howardites. From this they deduced that howardites did not all cool in the same way, and suggested that the intrusive melt rock (which they considered unique to Bununu) had been emplaced in the Bununu breccia after at least partial consolidation. In contrast, they considered that the high cooling rate determined for glassy bodies in Malvern limited their size relative to the 1 cm thick intrusive melt in Bununu.

Some of the conclusions reached by these important studies of glassy materials in Malvern and Bununu must be commented on in the light of the petrographic data presented in this chapter. KLEIN and HEWINS (1979) base much of their reasoning on what they consider the unique character of the intrusive body of melt rock in Bununu, but this relationship is not unique even within Bununu. A smaller (3.5 mm maximum width) mass of pale

brown glass with spherulitic devitrification principally at its margins occurs in the section of this howardite studied in the present investigation (NMNH 1571) and also in at least one of the sections examined by Klein and Hewins (USNM 1571-1), and appears to have been intruded into fairly fine-grained clastic 'matrix' (Plates 3.1 D, 3.2 E, and 3.4 C and D; Fig. 1 e and f, Klein and Hewins). Patches or lobes of 'matrix' are located within the boundaries of this body, just as in the intrusive melt rock, and its outlines are extremely irregular. It must be presumed that such an entirely glassy body had a cooling history different from that of the highly crystalline intrusive melt. According to the estimates of Klein and Hewins, a cooling rate of $1^{\circ}\text{C}/\text{min.}$ is required for the production of entirely glassy material of the Bununu composition whereas a rate of less than $0.1^{\circ}\text{C}/\text{min.}$ would be necessary for substantial crystallization to occur in the glass. Yet the spherulitic glass appears to have been sufficiently mobile, despite its faster cooling rate, to have intruded the 'matrix' of the meteorite, unlike the glassy droplets seen in Malvern that generally appear to have lost their plasticity entirely before incorporation in the breccia components. There are several examples of dark melt rocks in Malvern also that may have been intruded in a hot, partially plastic condition. These partially devitrified glassy microbreccias enclose lobate masses of 'matrix' and exhibit flow banding similar to that described by Klein and Hewins (p. 1128, and Fig 1 a and b). They have widths of up to 4 mm (cf. the spherulitic glass in Bununu). An example may be seen at the centre top of Plate 3.1 F.

A further point made by Klein and Hewins prompts discussion. They state (p. 1138): "There is as yet no evidence of more than one age of glass or melt rock in a single breccia." The present petrographic study of Malvern has shown examples of one type of glassy material included, wholly or partially, in another without fusion or deformation of the inclusion. This

presumably indicates complete solidification of the one glass prior to incorporation in the other, but does not give any information on the time interval between the formation of the two materials. Some, if not all, of the formational events may have occurred simultaneously; the actual process of incorporation may have taken place in flight following the impact that produced the melting. This appears particularly likely in the few instances observed in which one of the glassy constituents appears to have wrapped itself around the other. As Klein and Hewins pointed out, problems concerned with the relative ages of the glassy materials in a particular meteorite are likely to be solved only when the individual ages (and exposure ages) of these materials are determined.

3.5.3 Lithic clasts

Few studies have dealt specifically with the lithic clasts in achondrites. DUKE and SILVER (1967) observed that few fragments in howardites are large enough for magmatic textures to be distinguished, but noted that in Petersburg - an exception to that generalization - abundant fragments occur that resemble the eucrites Nuevo Laredo, Stannern, and Juvinas. One intergrowth of orthopyroxenes similar to a terrestrial pyroxenite was recorded from the same howardite. The paper by BUNCH (1975) drew a four-fold subdivision of the lithic clasts in howardites; some of these sub-types have been discussed in section 3.5.1, as have the rare diogenitic clasts assigned to the separate category of "meteorite clasts". The two categories not yet discussed comprise clasts that resemble eucrites. The first includes ophitic, sub-ophitic, intersertal, and variolitic types, while the second is made up of recrystallized "granular basalts and microgabbros". This part of Bunch's classification corresponds closely to the subdivision of the 'basaltic' fragments in Kapoeta made by DYMEK et al. (1976), but these writers did not describe

Bunch's 'mafic' and 'Al-rich' rocks as separate classes of lithic materials. Two of the four isotopically-dated clasts in their study were referred to the first category of 'basaltic' clasts (textures inferred to be volcanic), while the granular, recrystallized textures of the other two suggested an origin as deeper-seated rocks or as thermally-metamorphosed volcanics. The absence of definite anorthositic clasts in Kapoeta led Dymek and his colleagues to conclude that no source of such rocks existed on the Kapoeta parent body, suggesting that plagioclase fractionation did not play a major part in its evolution. The petrographic observations set out in this chapter extend this conclusion to the five meteorites with which it deals. Another point of similarity between the two investigations is the lack of evidence of olivine fractionation in the form of clasts of dunite-like rock. The rarity of such clasts in all howardites is even more striking than the scarcity of dominantly feldspathic lithic fragments.

PRINZ et al. (1977) drew attention to the possibility that some of the apparently igneous-textured lithic clasts found in achondritic breccias may, by analogy with lunar rocks of similar appearance, have been generated by impact melting (see their Figs 22 and 23). A few clasts that may be of this type were noted in the four recognized howardites included in the present study, but they are rare and of small size, and do not compare in importance with the glassy (and partially glassy) materials that are also regarded as having been produced by impact melting.

Further petrographic data on lithic clasts separated from the howardites Jodzie, Nobleborough (whose classification is problematical), Pavolvka, and Petersburg, and from the diogenite Johnstown were supplied by MITTLEFEHLDT (1979b) in a study that compared these clasts with lithic fragments from seven mesosiderites. Mittlefehldt qualitatively characterized these clasts according to their textural similarity to terrestrial analogues,

making an additional distinction in the eucrite-like clasts between rocks from shallow and from deep crystallization environments in order to facilitate their comparison with eucrites. From a petrographic point of view, the study suffers from the small number of lithic fragments investigated - most of the meteorites examined by Mittlefehldt are represented by a single clast - and from the assumption that a single crystal of pyroxene (Pavlovka) or plagioclase (Johnstown) is representative of a supposedly cumulate parent. These weaknesses apply also to the chemical aspects of the study, to which reference will be made in a later chapter.

Of more significance to the present investigation are some of the petrographic observations made on achondrites recently recovered from Antarctica, particularly from the Yamato Mountains. In contrast to non-Antarctic collections of achondrites, diogenites dominate the classified Antarctic achondrites collected in the period 1969-1979 (32 out of 62: REID, 1981, Table 2). It has been pointed out that, because of the nature of their occurrence on the ice, many of these diogenites may have originated from a single meteorite fall that disintegrated some distance above the surface (TAKEDA et al., 1978b). It is important that this question should be resolved because most of these Antarctic diogenites are texturally different from the previously-established concept of diogenites as monomict breccias, essentially pyroxenitic in composition and of possible cumulate origin, that had undergone little or no metamorphism. The majority of the Antarctic diogenites have a recrystallized, granoblastic texture in which no trace of cumulate layering has survived. This texture was observed in the first diogenite collected from the region - originally known as Yamato (b), but now named Yamato 6902 (OKADA, 1975; OKADA et al., 1975; TAKEDA et al., 1975). It was soon established that these unbrecciated diogenites do not resemble Tatahouine, the only other unbrecciated example hitherto recorded (TAKEDA et al., 1975). The narrow

compositional range of the pyroxenes in Antarctic diogenites is very similar to that of other diogenitic pyroxenes. An exception is Yamato 75032, which contains orthopyroxene and pigeonite that are considerably more Fe-rich (TAKEDA and MIYAMOTO, 1977; TAKEDA et al., 1979).

The recognition of meteorites of diogenitic composition that have undergone extensive recrystallization is of considerable significance to the present investigation, particularly with respect to formation of the howardites by the mixing of diogenitic and eucritic end-members. The extreme rarity of fragments of diogenite with the 'normal' texture of brecciated cumulate orthopyroxenites has been commented on in this and in other petrographic studies, because it is contrary to expectation if the two-component mixing hypothesis is valid. The abundance of mineral clasts of orthopyroxene in all howardites has been advanced by certain workers as an explanation of this anomalous situation, presumably on the grounds that these clasts originate from the disaggregation of cumulate diogenites. Even by itself this explanation does not fit all the facts because, as will be shown later, the clasts have a far wider compositional range than is present in diogenitic pyroxenes (including those from the Antarctic examples). Furthermore, orthopyroxene clasts in howardites do not show the degree of shock that might be expected from materials subjected to a process of sufficiently high energy to bring about the complete disintegration of igneous cumulates. It has been shown, in section 3.3.2 of this work and elsewhere, that these clasts tend to be almost euhedral, have only minor fracturing, and, in very many instances, show almost no shock effects whatsoever (Plate 3.8 A).

The situation becomes even more complex when the possibility is considered that the recrystallized, granoblastic type of diogenite encountered almost exclusively in the Antarctic collections constituted one of the major source rocks present at or near the surface of the achondrite parent body

during the formation of the regolith deposit from which the howardites were derived. The present petrographic study, and the literature reviewed, have indicated that recrystallized lithic clasts composed entirely, or almost entirely, of orthopyroxene do occur in howardites (e.g. in Bununu; see Plate 3.2 H), but they too are rare. Moreover, the disintegration of tough recrystallized pyroxenites such as the Yamato diogenites (assuming it could be accomplished) could not have produced the euhedral to subhedral orthopyroxene clasts that constitute a major component of all howarditic breccias. It must also be taken into account that an entirely different thermal history is indicated for the recrystallized diogenites by comparison with most of the other constituents of howardites, the majority of which have undergone no significant degree of post-crystallization re-heating.

A further revelation of importance to studies of the origin of the achondrites that has resulted from investigation of the Antarctic meteorites has been the prevalence of polymict eucrites, though, as for the diogenites, some of these may be related falls (REID, 1981). Previously, the only eucrite that had been shown to be polymict was Macibini (REID, 1974). The present writer suggested, on textural and compositional grounds, that this eucrite should be re-classified as a howardite (SIMPSON and AHRENS, 1979), a suggestion that will be returned to in later chapters. However, the realization that Macibini is not an isolated case has prompted a revision of the nomenclature of the basaltic achondrites (SCORE et al., 1982) in which a distinction is drawn between howardites and polymict eucrites on the basis of the presence, or relative absence, of Mg-rich pyroxene. This criterion does not, in my opinion, support the classification of Macibini as a eucrite because of the very wide range of pyroxene compositions recorded by REID (1974) and given as $En_{81} - En_{39}$ by MASON et al. (1979). The entire question of the classification of the basaltic achondrites will be returned to at a

later stage, but, from the observations of REID (1982), there appears to be a great similarity between the lithic clasts present in the Antarctic polymict eucrites and those in howardites. Both clast populations are dominantly eucritic and the textural evidence indicates rapid cooling in a surface (or near-surface) environment. Neither suite of lithic clasts was subjected to severe shock, and fragments showing metamorphic effects are in a minority.

3.5.4 The chondritic component in howardites

As noted previously, the present investigation has established the virtual absence of chondritic material that can be discerned with the microscope in the five achondrites studied. BUNCH (1975) arrived at the same conclusion, except that he found carbonaceous chondrite fragments in Kapoeta and Washougal. Further work (BUNCH et al., 1976) established the presence of similar C2 carbonaceous chondrite inclusions in Jodzie. CHOU et al. (1976) postulated the presence of 2.4% - 3.3% chondritic material, characterized as similar to CM carbonaceous chondrites, in Malvern, Kapoeta, Bununu, and Bholgati. This conclusion was based on a study of siderophile and volatile trace elements, and was not supported by petrographic observations. Papers by WILKENING (1977) and ANDERS (1978) re-stated the inclusion of C2 carbonaceous chondrite material (CM, if the classification system of WASSON (1974) is used) in Kapoeta and Jodzie. No other information on the chondritic component in howardites has been found in the recent literature surveyed. The writer is therefore forced to conclude that the "numerous features reminiscent of chondrites found in howardites (in particular in the gas-rich ones)" by JEROME and GOLES (1971) have escaped the notice of most other workers, including himself.

3.5.5 Metals

In Chapter 2, mention was made of the work of LOVERING (1964) and DUKE (1965) on the metal phase in the basaltic achondrites. Prior to these studies, the only data on achondritic metal related to Kapoeta (FREDRIKSSON and KEIL, 1963), in which kamacite and taenite were observed in both 'light' and 'dark' lithologies. Fredriksson and Keil noted that some of the kamacite in the 'dark' portions of Kapoeta had been mechanically deformed and shocked. Duke's study showed that metal occurs in the achondrites either as irregular grains interstitial to the silicates, or as oriented inclusions within pyroxenes. He interpreted the first as primary, the second as possibly resulting from reduction of pyroxene. A third texture - silicate-metal intergrowths - occurs in some recrystallized lithic clasts in howardites, or around the rims of these clasts. The kamacite in some of these intergrowths shows signs of distortion and recrystallization. FROST (1971) reported irregular grains of kamacite in Molteno that appear, from his description, to be in the 'matrix', and suggested that the metal is later in origin than the ilmenite and troilite in the howardite. A "sizeable mass" of kamacite rimming a chondrule-like clast composed mainly of orthopyroxene was observed in Washougal by JÉROME and CHRISTOPHE MICHEL-LÉVY (1972). JÉROME and DESNOYERS (1974) noted the occurrence of metal grains in some of the glasses in Malvern and suggested that they originated from a chondritic projectile that generated the glasses. The same authors later (1977) commented on the rarity of metal in the so-called 'light lithology' of Malvern; they found only one polycrystalline fragment, which consisted of taenite rimmed by kamacite. In the glassy materials ('dark lithology'), however, metal is more abundant, and is dominantly kamacite. The obliteration of Neumann bands at the margins of some kamacite grains was ascribed by Desnoyers and Jérôme to a brief heating episode at the time of formation of the glass, suggesting that the metal

was not formed by reduction of the glass but was incorporated in it as particles. They reported that metal occurs only as rare, minute grains in recrystallized parts of the large 'eucritic' fragment in Malvern, and might therefore be of secondary origin. Kamacite and taenite were identified in the Antarctic howardite Yamato 7308 by MIYAMOTO et al. (1978), while OLSEN et al. (1978) recorded kamacite from the polymict eucrite Allan Hills 7605. GOOLEY and MOORE (1976) described the characteristics and occurrence of the metal phases in eight non-Antarctic diogenites, and a less comprehensive account of the Ni-poor, Co-rich metals of the Yamato diogenites was given by TAKEDA et al. (1978b). The only description of metal in a cumulate eucrite (Moama) shows that it occurs in close association with troilite as inclusions in pyroxenes and fracture-fillings in plagioclases (LOVERING, 1975). This occurrence was interpreted as indicative of crystallization from a late-stage, immiscible Fe-FeS melt.

More specialized studies of the metals in howardites have recently been published. Preliminary results were reported by HEWINS (1978), who studied the metals in seven howardites according to their mode of occurrence - in melt rocks, in the 'matrix', or as primary grains in pyroxenes and lithic clasts. The investigation concluded that primary metals are Ni-poor, whereas those in glassy melt rocks are Ni-rich, with the characteristics of meteoritic metal (HEWINS, 1979a). Bununu, Kapoeta, and Malvern contain similar Ni-rich metal in the 'matrix' (as does Bholgati, although it has no observed melt rocks). This was interpreted by Hewins as evidence of impact by high-velocity projectiles in the case of these four howardites only. He further concluded, from the identity of the primary and 'matrix' metal in many howardites, and from the variability of the primary metal from howardite to howardite, that each of these meteorites came from a different source region. A separate study of Malvern (HEWINS and KLEIN, 1978) noted the rarity of primary metal

in mineral and lithic clasts and suggested two alternative modes of origin for the meteoritic-type metal in the melt rocks and the 'matrix'. An origin involving metal-bearing projectiles impacting at high velocities was preferred. The alternative - introduction of the metal by reduction of lower-velocity carbonaceous chondrite projectiles - was not favoured because of lack of evidence.

The present investigation includes only limited petrographic data on metals (section 3.3.3). The solitary grain observed in Binda occurs interstitially to the silicates, and is most probably primary (cf. DUKE, 1965; REID et al., 1970). This occurrence is different from that reported from the cumulate eucrite Moama by LOVERING (1975). The rare glassy materials in Binda are devoid of metal. Similarly, the present study did not record metal from the glasses or glassy microbreccias in Bununu, but the more comprehensive investigation of HEWINS (1979a) reported its occurrence intergrown with troilite in tiny spherules in fairly coarsely-crystalline impact melt rocks that I may not have recognized as such. Metal inclusions in pyroxenes in Bununu appear to be primary, as concluded also by Hewins. This applies also to similar occurrences in the pyroxenes of Malvern and Molteno, and to metal in cumulate-textured lithic clasts in Malvern. There is less clarity, however, on the origin of the metal grains present in the 'matrix' of Bununu, Frankfort, Malvern, and Molteno. Many of these grains are irregularly-shaped and appear to penetrate, or infiltrate, the surrounding fragmental materials. If this observation is correct, i.e. if the mechanism involved was intrusion and not replacement, it could provide support for the hypothesis of high-velocity impact by metal-bearing projectiles on the source regions of Bununu and Malvern (HEWINS and KLEIN, 1978; HEWINS, 1979a) and extend it to Frankfort and Molteno, howardites not studied by these authors. The compositional evidence is critical in this regard, and is considered in Chap. 7.

From the present study and accounts in the literature, it is evident that the basaltic achondrites with the highest contents of metal are those that contain glassy materials of impact origin, and that the bulk of the metal is concentrated in these impact-derived melts. These observations strengthen the postulated derivation of much of the metal in these meteorites from impacting projectiles (DESNOYERS and JÉROME, 1977; HEWINS and KLEIN, 1978; HEWINS, 1979a). The irregular, sub-spherical metal mass in Molteno that includes orthopyroxene crystals and fine-grained 'matrix' materials may have formed part of such a projectile that was melted and dispersed in the impact. The larger kamacite mass with pyroxene inclusions reported from Washougal by JÉROME and CHRISTOPHE MICHEL-LÉVY (1972) may have had a similar history.

3.5.6 The mixing hypothesis of howardite origin

The suggestion that howardites are mixtures of two components - eucrites and diogenites - in varying proportions, first advanced by JÉROME and GOLES (1971) and later supported by McCARTHY et al. (1972), received further attention in the literature during the period of the present investigation. An important account was given of the meteorite Aïoun el Atrouss, which closely approximates an ideal two-component mixture of diogenite and at least 7% (volume) of eucritic inclusions (LOMENA et al., 1976). No clasts of intermediate composition were observed, and the meteorite therefore bears little resemblance even to highly magnesian howardites such as Frankfort. No chondritic material was reported. DUKE (1978) examined the eucritic inclusions in more detail and confirmed the observation of the earlier investigation that they are of two textural types, the one igneous, the other granoblastic and attributed to thermal metamorphism by Lomena and his colleagues. Duke established that both types may exist in the same included clast, and

that they are mineralogically and compositionally very similar. He concluded that a eucritic breccia with clasts of various textures was slowly annealed, possibly by deep burial in a hot deposit of impact ejecta, prior to further brecciation and mixing with diogenitic material at a low temperature, as indicated by the lack of thermal effects in the meteorite as a whole. In the present study, eucritic fragments with granoblastic textures suggesting subsolidus recrystallization were encountered in all the meteorites except Binda, but clear evidence similar to that of Duke that clasts of this type may have been derived from the same source region as those with extrusive or hypabyssal textures was not found.

During the course of the current investigation, several papers were published that present petrographic evidence against the formation of howardites by mixing of eucritic and diogenitic components only; chemical evidence will be discussed after presentation of the analytical data obtained by this study. The preliminary work of SIMPSON (1975) showed that a wide range of components, probably related by igneous differentiation, had been produced and mixed by impact processes to form Malvern. A still wider range of related materials had been reported from Macibini (classed as a eucrite) by REID (1974). BUNCH (1975) also concluded, from petrographic and compositional considerations, that howardites are made up of a variety of possibly related materials. The study of Kapoeta (DYMEK et al., 1976) also recognized the presence of a wide spectrum of related source materials, some of which do not correspond to known meteorite types. TAKEDA et al. (1976) interpreted the results of their study of the crystallographic and chemical features of achondritic pyroxenes as indicative of a single-step differentiation process in the parent body that implied a continuum of compositions in the source materials mixed to form the howardites.

The petrographic data of the present investigation have confirmed the earlier observations on Malvern (SIMPSON, 1975) and extended them to Bununu, Frankfort, and Molteno. In all of these (which are acceptably classified as howardites), the optical characteristics of the main minerals and the varied textures of the lithic clasts strongly suggest a wide diversity of source materials. One of the main uses of the phase chemical data presented in Chap. 6 of this report is the confirmation of the petrographic observations and determination of the extent of the compositional variability of the components of these meteorites. Conversely, the petrographic study of Binda indicates that, to a first approximation, it is monomict, apparently having originated as an igneous cumulate that was subsequently brecciated in situ. From this observation, wide ranges in composition would not be expected from the constituent phases in Binda.

3.6 SUMMARY AND CONCLUSIONS OF THE PETROGRAPHIC INVESTIGATION

The following observations and conclusions are based principally on the comparative petrographic study of five achondrites presented in the foregoing chapter, but published work on these and other achondrites has been used to extend the scope and applicability of the conclusions.

- (1) All five meteorites studied are pyroxene-plagioclase breccias. All contain materials that are, or have originally been, glassy, but in widely varying amounts; in Binda and Frankfort they occur in very minor amounts. Other widespread but minor constituents are ilmenite, chromite, troilite, and metal; tridymite and olivine occur, but are neither widespread nor common. Mineral fragments make up the bulk of the crystalline material. Lithic clasts, which display a variety of igneous and metamorphic textures, are in a small minority except in Binda. No sorting or stratification of the fragmental constituents is

present, and the breccias have undergone only the lowest grades of lithification. Most of the components exhibit shock effects, but these are not severe.

- (2) The variety of constituents and their lack of compositional homogeneity show that four of the achondrites (Bununu, Frankfort, Malvern, and Molteno) are polymict breccias. Binda appears to be monomict, despite its small content of possibly exotic glassy material, because its main minerals (magnesian orthopyroxene and calcic plagioclase) show little optical variation whether they occur in lithic clasts or in the remainder of the meteorite.
- (3) The agency that produced the brecciation in all five meteorites is presumed to have been impact because of the shock effects observed and the presence of glasses and impact melt rocks. The impacting projectile may have been metal-bearing in the case of the four definite howardites studied, but Binda is devoid of metal that could be attributed to such a source.
- (4) Bununu, Frankfort, Malvern, and Molteno, in common with other howardites described in the literature, appear to represent well-mixed, lithified samples of a regolith-type deposit that covered the surface of the parent body (assuming all originated on one body). The source rock for Binda, however, was an orthopyroxene-plagioclase cumulate that was shattered in situ with only minimal admixture of extraneous material, and may therefore never have formed part of a regolith. Petrographically, therefore, there is little to suggest a genetic link between Binda and any of the howardites yet described, either in this work or in the literature.
- (5) The four howardites studied (and all meteorites that originate in a regolith deposit) bear the imprint of at least two impact events -

that which caused the brecciation followed, after an indefinite time interval, by the impact responsible for excavation and ejection of the meteorite. Evidence of at least three such events is preserved in Malvern in the form of the large microbreccia clast. Should the devitrified glass in this microbreccia pre-date its formation, then Malvern contains a record of at least four impact events.

- (6) The glassy materials in the five meteorites investigated were formed, in part at least, during impact events that produced the regolith deposit that was subsequently mixed and lithified. These glassy materials have irregular boundaries and may intrude the 'matrix' and enclose parts of it. Many glassy bodies have also incorporated much fine-grained 'matrix' material identical in appearance to that surrounding them. The smooth, regular outlines of other glasses indicate, however, that they did not 'splash' into the regolith, but had previously solidified. These non-intrusive glassy materials may contain a few inclusions of pyroxene or plagioclase but have not, in general, incorporated 'matrix'. Some show evidence of plasticity and flow and, in rare instances, of partial incorporation of other glasses, probably while in flight. The division into intrusive and non-intrusive glassy materials cuts across their classification into 'true' glasses and glassy microbreccias, although the majority of 'true' glasses are non-intrusive.
- (7) Many of the glassy materials have devitrified to a greater or lesser extent. The presence of abundant quench crystals (orthopyroxene microlites) indicates that partial devitrification took place in some glasses very soon after their formation. This is evident in many of the 'true' glasses, but other workers have shown the presence of pyroxene microlites in the dark glassy matrices of at least some of

the glassy microbreccias, in which quenching may have resulted from cooling caused by incorporation of large amounts of 'matrix' and coarser-grained clasts. A second type of devitrification may be seen, particularly in the glassy microbreccias. This devitrification, which may have taken place at lower temperature, results in a grey cryptocrystalline material containing relics of included mineral and lithic clasts, and is attributable to complete crystallization of the dark brown glassy matrix material of the glassy microbreccias. Transitional stages in this process are readily distinguishable because of the gradual colour change that takes place.

- (8) Zonation of pyroxene and plagioclase is conspicuously absent in all five meteorites studied, regardless of the modes of occurrence of these minerals. This suggests that many of the source rocks cooled slowly under conditions of equilibrium crystallization, but the presence of abundant uninverted pigeonite in the four howardites is indicative of rapid cooling in the rocks from which they were derived. The inference to be drawn from these observations is that materials are present in howardites that represent two separate suites of source rocks that crystallized under entirely different cooling conditions. Binda contains no uninverted pigeonites and presumably represents a single cooling environment.
- (9) The morphology of the pyroxene and plagioclase crystal clasts that are predominant in howardites is consistent with derivation from cumulates. The presence of similar clasts of these minerals in Binda, which is interpreted as a brecciated pyroxene-plagioclase cumulate, demonstrates the feasibility of such an origin for these clasts. The observed lack of zonation in the minerals supports this suggestion.

- (10) The contribution made by lithic clasts of eucritic appearance is small, even in relatively Mg-poor howardites such as Malvern, and none of the crystal clasts of clinopyroxene or plagioclase give the impression of having originated in fine-grained rocks with ophitic or subophitic textures. If such material is present, it must be in the 'matrix' in a very finely-divided form and must therefore be volumetrically of lesser importance than the coarser clasts that appear to have been derived from cumulates. This strongly suggests the possibility that the contribution to howarditic breccias made by source rocks similar to cumulate eucrites may outweigh that of eucrites considered, on the basis of textural evidence, to represent liquids, e.g. Juvinas and Sioux County. The role that may be played by the 'unequilibrated' eucrites (REID and BARNARD, 1979) in the formation of the howardites will be discussed in a later chapter.
- (11) The possibility exists that some of the plagioclase clasts may have come from the disintegration of anorthositic source rocks. Small lithic clasts composed entirely of plagioclase are of commoner occurrence than possible clasts of diogenite, which is regarded as a major source of magnesian pyroxene for the howardites. However, as no anorthositic meteorites have ever been recorded (assuming that some estimates of the plagioclase content of Serra de Magé have been based on unrepresentative samples), it is generally supposed that plagioclase fractionation played little or no part in the genesis of the differentiated rocks from which howardites were formed. The petrographic study reported did not find any definite evidence to cause this view to be modified.
- (12) The rarity of orthopyroxenite lithic clasts that might be interpreted as a diogenitic contribution has been noted in the howardites described in this chapter and in virtually all other published petrographic

descriptions of howardites. This applies not only to clasts that may have originated from diogenites with the cumulate texture regarded until recently as normal for this type of meteorite but also to clasts of recrystallized pyroxenite that may represent the granoblastic type of diogenite commonly found in the Antarctic collections. The petrographic evidence therefore militates strongly against diogenites sensu stricto being important contributors to howarditic breccias. Compositional data to be presented in a later chapter supports this conclusion.

- (13) Recognizable chondritic material is virtually absent from the howardites studied and is reported, in very minor amount, only in published descriptions of Kapoeta and Jodzie. It is therefore concluded that the contribution made to howardites by a chondritic component is volumetrically insignificant unless the chondritic material is dispersed in a finely-divided form throughout the 'matrices' of these meteorites.
- (14) The petrographic data from Bununu, Frankfort, Malvern, and Molteno do not support the hypothesis that howardites are mechanical mixtures, in varying proportions, of a eucritic and a diogenitic component, with a chondritic contribution to restore the chemical balance in the resultant mixtures. The small proportion of definitely eucritic material present, the extreme rarity of possibly diogenitic clasts, the virtual absence of a chondritic component, and the preponderance of mineral clasts that cannot unequivocally be ascribed to either of the proposed end-members of the mixing series, all point to the conclusion that the model, as originally formulated, is not valid.
- (15) The petrographic investigation does, however, clearly indicate that howardites are mechanical mixtures. By analogy with lunar breccias, they were probably formed by lithification of an impact-generated

regolith deposit at the surface of the parent body. Their constituents have not been subjected to high temperatures or high degrees of shock. Exotic materials do occur in the breccias, but in very minor amounts. The petrography of the components suggests that they may be related by igneous processes. It is the purpose of the compositional studies presented in later chapters to investigate the nature of these relationships.

CHAPTER 4

BULK CHEMICAL COMPOSITIONS OF THE ACHONDRITES AND MESOSIDERITES INVESTIGATED

Get your facts first, and then you can
distort them as much as you please.

Mark Twain (1835-1910)

4.1 INTRODUCTION

The purpose of this chapter is to present the compositional data obtained by XRF analysis of five samples of achondrites and the non-magnetic fractions separated from seven mesosiderites, as specified in Table 1.1. These basic data were recalculated to facilitate comparison, and the recalculated analyses also are presented. In addition, details are given of check analyses carried out during the investigation, and published analyses of achondrites and mesosiderites that were used to supplement the original XRF data are tabulated for ease of reference. CIPW norms were calculated for all the analyses used (in their recalculated versions) in the investigation, and these norms are presented in summarized form. The chapter ends with a preliminary discussion of observations made on the compositional and normative data presented.

4.2 THE ORIGINAL DATA

Details of the techniques of sample preparation employed in this study are given in Appendix 6. All analyses of bulk samples for major, minor, and trace elements were carried out using X-ray fluorescence (XRF) spectrometry. A brief account of the analytical techniques employed

appears in Appendix 7, which contains also particulars of the standardization and the consequent accuracy of the analyses, and estimates of the precisions of the various oxide and element determinations and their associated detection limits. All samples were analyzed for 23 elements. Values for loss (or gain) on ignition and H_2O were determined also. The achondrite analyses are presented in Table 4.1, while Table 4.3 lists the analytical data on the non-magnetic fractions of the mesosiderites studied.

4.3 THE RECALCULATED DATA

Appendix 6 details the procedure followed to separate the metal and non-magnetic fractions of the mesosiderites without significant loss of silicate material. The magnetic separation did not, however, remove all the metal present in the crushed samples, and troilite, which is very weakly magnetic in comparison to metal, was assumed to have remained in the samples. Visual inspection of the magnetic extracts suggested this was indeed the case, and the high concentrations of S detected in the analyzed samples further confirm the assumption (Table 4.3). The mesosiderite analyses were therefore recalculated to correct for metal and troilite residues. The recalculation procedure is explained in Appendix 9. The recalculated analyses, prior to normalization of the silicate fractions to 100%, indicate the amounts of metal and troilite that remained in the samples analyzed (Appendix 9, Table A9.2). In order to make comparison between the achondrites and the silicate fractions of the mesosiderites more meaningful, the achondrite analyses of Table 4.1 were similarly recalculated (Table A9.1). The final (i.e. recalculated and normalized) versions of the achondrite analyses appear in Table 4.2, and Table 4.4 lists the corresponding versions of the mesosiderite analyses. The data contained in these two tables are those that are used in all calculations, comparisons, and diagrams in

Table 4.1. Chemical analyses of five achondrite samples: the original data

	MALVERN (UCT)	MALVERN (BLM)	BINDA	KAPOETA	MOLTENO
SiO ₂	49.16	48.66	49.98	49.79	49.36
TiO ₂	0.503	0.526	0.234	0.384	0.442
Al ₂ O ₃	10.01	10.61	7.05	8.13	8.95
Cr ₂ O ₃	0.573	0.561	0.745	0.778	0.683
FeO*	18.41	18.92	16.75	17.30	17.97
MnO	0.534	0.520	0.518	0.515	0.523
MgO	11.75	10.98	17.58	15.81	14.01
CaO	8.07	8.46	5.50	6.46	7.20
Na ₂ O	0.31	0.31	0.15	0.29	0.29
K ₂ O	0.039	0.043	0.009	0.011	0.017
P ₂ O ₅	0.058	0.071	0.025	0.045	0.050
L.O.I.	(-1.747)	(-1.829)	(-0.818)	(-0.739)	(-1.072)
H ₂ O-	0.171	0.193	0.189	0.154	0.102
Ni	0.024	0.020	0.000	0.023	0.022
S	0.159	0.341	0.121	0.286	0.295
	99.771	100.215	98.851	99.976	99.914
O ≡ Ni in metal	0.007	0.005	0.000	0.006	0.006
O ≡ S	0.080	0.171	0.061	0.143	0.148
TOTAL	99.684	100.039	98.790	99.827	99.760
Rb	<0.9	<0.9	<0.9	<0.9	<0.9
Ba	26	23.5	9.0	17.7	20.1
Sr	56	59	31	45	51
Zr	40	32	14.0	28	**
Nb	4.9	<2.1	<2.0	3.5	3.2
Y	14.1	9.8	6.4	10.5	13.4
(Cr)	3802	3715	4614	4579	4115
V	90	**	102	98	90
Ni	236	203	5.3	233	224
Co	19.6	18.3	6.6	22.1	22.5
Cu	**	30	4.6	**	**
Zn	7.4	13.7	16.8	6.9	27

Notes (applicable also to Table 4.3):

1. The major element analyses are the mean of four separate analyses carried out on two fusion discs.
2. The trace element analyses are the mean values obtained from three determinations performed on a single pressed-powder briquette.
3. FeO* - all Fe expressed as FeO.
4. L.O.I. values enclosed in parentheses indicate a gain on ignition, and are ignored in the summation.
5. (Cr) - Cr determined as a trace element; included for comparative purposes only.
6. All trace element data are expressed as parts per million (ppm).
7. ** - value suspected to have been enhanced by contamination.
8. The analytical precisions determined for the various oxides (Table A7.1) allow some, but not all, to be quoted to the third decimal place. In this and other tables, therefore, the third figure after the decimal point in the totals results from summation but is not regarded as significant.

Table 4.2. The data of Table 4.1, recalculated on a metal-free, troilite-free, and volatile-free basis

	MALVERN (UCT)	MALVERN (BLM)	BINDA	KAPOETA	MOLTENO
SiO ₂	49.91	49.44	50.86	50.70	50.21
TiO ₂	0.511	0.534	0.238	0.391	0.450
Al ₂ O ₃	10.16	10.78	7.17	8.28	9.10
Cr ₂ O ₃	0.582	0.570	0.758	0.792	0.695
FeO*	17.76	17.96	16.77	16.29	17.07
MnO	0.542	0.528	0.527	0.524	0.532
MgO	11.93	11.16	17.89	16.10	14.25
CaO	8.19	8.60	5.60	6.58	7.32
Na ₂ O	0.32	0.32	0.15	0.30	0.30
K ₂ O	0.040	0.044	0.009	0.011	0.017
P ₂ O ₅	0.059	0.072	0.025	0.046	0.051
	100.004	100.008	99.997	100.014	99.995
Rb	<0.9	<0.9	<0.9	<0.9	<0.9
Ba	26	23.9	9.2	18.0	20.4
Sr	57	60	32	46	52
Zr	40	33	14.2	29	**
Nb	5.0	<2.1	<2.0	3.6	3.3
Y	14.3	10.0	6.5	10.7	13.6
(Cr)	3860	3774	4695	4662	4186
V	92	**	103	99	92

Notes (applicable also to Table 4.4):

1. For explanation of the recalculation procedure, see Appendix 9.
2. FeO* - all Fe in the silicates expressed as FeO.
3. (Cr), ** - see Notes for Table 4.1.
4. All trace element values are expressed as ppm.

Table 4.3. Chemical analyses of the non-magnetic fractions of seven mesosiderites: the original data

	MINCY	PATWAR	ESTHER- VILLE	MOUNT PADBURY	VACA MUERTA	EMERY	ŁOWICZ
SiO ₂	47.46	40.49	47.81	44.32	36.19	49.81	50.12
TiO ₂	0.263	0.182	0.283	0.234	0.214	0.365	0.342
Al ₂ O ₃	6.69	6.35	8.99	6.69	7.14	11.45	10.58
Cr ₂ O ₃	1.474	0.534	0.835	0.863	0.903	0.790	0.767
FeO*	16.78	28.25	17.25	23.06	30.51	12.92	13.36
MnO	0.530	0.448	0.464	0.506	0.354	0.509	0.533
MgO	18.27	12.96	15.77	15.15	10.08	12.02	13.85
CaO	5.29	5.21	6.76	5.20	5.62	8.79	7.97
Na ₂ O	0.22	0.19	0.29	0.15	0.20	0.36	0.31
K ₂ O	0.008	< 0.002	0.003	0.003	0.010	0.015	0.017
P ₂ O ₅	1.243	0.902	0.524	0.401	1.407	2.134	1.325
L.O.I.	(-0.525)	1.163	(-0.583)	0.870	2.771	(-0.455)	(-1.151)
H ₂ O-	0.100	0.052	0.042	0.111	0.137	0.199	0.126
Ni	0.470	0.105	0.161	0.415	0.531	0.272	0.350
S	0.544	6.906	1.803	3.058	6.108	0.406	0.246
	99.342	103.742	100.985	101.031	102.175	100.040	99.896
O ≡ Ni in metal	0.128	0.029	0.044	0.113	0.145	0.074	0.095
O ≡ S	0.272	3.453	0.902	1.529	3.054	0.203	0.123
TOTAL	98.942	100.260	100.039	99.389	98.976	99.763	99.678
Rb	<0.9	<1.1	<2.2	<2.6	<1.5	<1.1	<1.1
Ba	11.2	5.7	12.7	6.8	5.9	17.9	15.0
Sr	32	32	45	29	35	57	54
Zr	14.5	12.2	9.8	4.4	12.5	17.1	16.3
Nb	<2.0	<2.5	<2.2	<2.5	<2.4	<1.8	<1.8
Y	6.8	6.9	<2.2	<2.5	9.1	10.3	8.6
(Cr)	8079	2895	4435	4736	5480	4930	4780
V	141	73	83	96	88	92	94
(Ni)	3585	860	732	4473	6275	2142	2104
Co	105	21.4	39	131	323	71	28
Cu	2.4	24.9	40	36	43	<1.7	<1.7
Zn	<1.4	3.3	6.0	<1.2	<1.7	<1.1	1.3

Table 4.4. The data of Table 4.3, recalculated on a metal-free, troilite-free, and volatile-free basis

	MINCY	PATWAR	ESTHER- VILLE	MOUNT PADBURY	VACA MUERTA	EMERY	ŁOWICZ
SiO ₂	53.20	51.38	51.49	54.38	50.36	53.21	53.76
TiO ₂	0.295	0.231	0.305	0.287	0.298	0.390	0.367
Al ₂ O ₃	7.50	8.06	9.68	8.21	9.94	12.23	11.35
Cr ₂ O ₃	1.652	0.678	0.899	1.059	1.256	0.844	0.823
FeO*	8.71	14.64	11.98	9.80	13.57	7.86	7.95
MnO	0.594	0.568	0.500	0.621	0.493	0.544	0.572
MgO	20.48	16.45	16.98	18.59	14.03	12.84	14.86
CaO	5.93	6.61	7.28	6.38	7.82	9.39	8.55
Na ₂ O	0.25	0.24	0.31	0.18	0.28	0.39	0.33
K ₂ O	0.009	<0.002	0.003	0.004	0.014	0.016	0.018
P ₂ O ₅	1.393	1.145	0.564	0.492	1.958	2.280	1.421
TOTAL	100.013	100.002	99.991	100.003	100.019	99.994	100.001
Rb	<0.9	<1.1	<2.2	<2.6	<1.5	<1.1	<1.1
Ba	12.6	7.2	13.7	8.3	8.2	19.1	16.1
Sr	36	40	49	35	49	61	58
Zr	16.3	15.5	10.6	5.4	17.4	18.3	17.5
Nb	<2.0	<2.5	<2.2	<2.5	<2.4	<1.8	<1.8
Y	7.6	8.8	<2.2	<2.5	12.7	11.0	9.2
(Cr)	9055	3674	4777	5811	7624	5266	5127
V	158	93	90	118	123	98	101

subsequent chapters. Small differences (i.e. in the second decimal place) arising from minor refinements to the recalculation procedure exist between some of the values in Table 1 of SIMPSON and AHRENS (1977) and the corresponding data in Tables 4.2 and 4.4; the preferred values are those given in this report.

4.4 CHECK ANALYSES

The remarkable constancy of the Ca/Al ratio in meteorites has been a source of interest for about the last decade. The lack of fractionation of this ratio in the chondrites was noted by AHRENS et al. (1968), and its identity in chondrites and basaltic achondrites was established by AHRENS and VON MICHAELIS (1969a). On the basis of published analyses, however, MCCARTHY and AHRENS (1971) concluded that the ratio is distinctly lower in the mesosiderites (0.88) than in the howardites (1.08). A review of the mesosiderites by MASON and JAROSEWICH (1973) appeared to support this conclusion, but the data of BEGEMANN et al. (1976) were not unequivocal on the subject. The data obtained during the present investigation indicate that Ca/Al ratios for the mesosiderites lie in the range 1.02-1.11. The average ratio (1.05) closely approximates the mean value for chondrites and basaltic achondrites.

It was desirable, therefore, that prior to publication of preliminary results on the investigation of the mesosiderites (SIMPSON and AHRENS, 1977), an independent check should be carried out on the mesosiderite analyses to safeguard against the possibility of error, e.g. in the flux used in the preparation of the fusion discs that were analyzed. To this end, aliquots of the silicate fractions of Vaca Muerta and Łowicz were sent to Mr E. Jarosewich of the Department of Mineral Sciences, Smithsonian Institution, Washington D.C., and to Dr J.M. Rhodes, Lockheed Electronics,

Johnson Space Center, Houston. Both are internationally-known analysts, and kindly carried out the check analyses requested of them, the former by classical 'wet' chemical techniques, the latter by XRF methods similar to those employed at the University of Cape Town. Their results are set out in Table 4.5 for comparison with the original analyses (Table 4.3). The completeness of the analyses performed by Jarosewich enabled their recalculation and normalization in a way similar to the U.C.T. analyses, and direct comparisons can be made between these recalculated checks (Table 4.6) and the corresponding data in Tables A9.2 and 4.4. The degree of agreement between the original analyses and the checks will be discussed in a later section of this chapter.

4.5 SUPPLEMENTARY DATA FROM THE LITERATURE

The programme of bulk chemical analysis undertaken as part of the present investigation was not aimed at a wide coverage of the achondrites, but was intended rather to supplement previous studies carried out by this Department. In some parts of the investigation (e.g. SIMPSON and AHRENS, 1977), these new analyses were sufficient when used in conjunction with the mesosiderite data. In others, however, where a broader view of the achondrites was required (e.g. SIMPSON and AHRENS, 1979), recourse to the literature became necessary. Similarly, two mesosiderite analyses were selected to widen the coverage of these meteorites. To facilitate reference to these supplementary data, which are scattered throughout the recent literature, the analyses are listed in their original form in Tables 4.7 - 4.9. Where possible, they were recalculated to represent the 'silicate' (i.e. silicates + oxides) fractions of the meteorites. These recalculated analyses appear in Table 4.10. The data from 42 bulk analyses were therefore used in the investigation. Table 4.11 sets out the concentration ranges present in these data. Published trace element data appear in Table 4.19.

Table 4.5. Chemical analyses of the non-magnetic fractions of two mesosiderites, carried out as an independent check on the data of Table 4.3

	VACA MUERTA		ŁOWICZ	
	Jarosewich	Rhodes (mean of 2 analyses)	Jarosewich	Rhodes (mean of 2 analyses)
SiO ₂	37.70	37.84	50.33	48.54
TiO ₂	0.21	0.24	0.36	0.33
Al ₂ O ₃	7.20	7.39	10.60	10.30
Cr ₂ O ₃	0.87	n.d.	0.71	n.d.
Fe ₂ O ₃	9.01	--	--	--
FeO	8.98	30.87	12.39	13.25
MnO	0.34	0.40	0.51	0.56
MgO	10.21	10.17	14.08	13.42
CaO	5.82	5.75	8.12	7.89
Na ₂ O	0.23	n.d.	0.31	n.d.
K ₂ O	<0.02	0.03	<0.02	0.03
P ₂ O ₅	1.39	1.33	1.30	1.17
L.O.I.	2.61		0.56	
H ₂ O-	0.18		0.06	
C	0.05		0.14	
Ni	0.57	n.d.	0.34	n.d.
S	--	0.02	--	0.00
FeS	15.30		0.63	
TOTAL	100.67	94.04	100.44	95.49
Total Fe	23.00		10.03	

n.d. - not determined.

Table 4.6. Recalculation and normalization of the check analyses of Vaca Muerta and Łowicz carried out by E. Jarosewich, Smithsonian Institution

	VACA MUERTA		ŁOWICZ	
	Recalc.	Normalized	Recalc.	Normalized
SiO ₂	37.70	50.70	50.33	53.85
TiO ₂	0.21	0.28	0.36	0.39
Al ₂ O ₃	7.20	9.68	10.60	11.34
Cr ₂ O ₃	0.87	1.17	0.71	0.76
Fe ₂ O ₃	9.01	12.12	--	--
FeO	1.38	1.86	7.14	7.64
MnO	0.34	0.46	0.51	0.55
MgO	10.21	13.73	14.08	15.07
CaO	5.82	7.83	8.12	8.69
Na ₂ O	0.23	0.31	0.31	0.33
K ₂ O	<0.02	<0.02	<0.02	<0.02
P ₂ O ₅	1.39	1.87	1.30	1.39
TOTAL	74.36	100.01	93.46	100.01
L.O.I.	2.61		0.56	
H ₂ O-	0.18		0.06	
C	0.05		0.14	
NiFe	6.48		4.42	
FeS	15.30		0.63	
'Excess' O*	1.54		1.08	
TOTAL ⁺	100.52		100.35	

⁺ Total adjusted for O $\equiv$ Ni in metal in the original analysis (Table 4.5).

* For an explanation of 'excess' O, see Appendix 9.

Table 4.7. Published analyses of achondrites classified as eucrites that are used to supplement the original data of the present investigation

Meteorite	ALLAN HILLS 7605	BÉRÉBA	CACHARI	HARAIYA	JUVINAS	LAKAN- GAON	MACIBINI
Source	1	2	2	2	2	3	2
SiO ₂	48.92	49.14	48.26	48.69	49.35	49.03	49.33
TiO ₂	0.73	0.704	0.632	0.559	0.639	0.847	0.717
Al ₂ O ₃	12.22	12.75	12.85	12.49	13.00	11.55	12.11
Cr ₂ O ₃	0.39	0.32	0.32	0.32	0.34	0.316 ⁺	0.42
FeO*	17.56	19.08	19.10	19.26	18.82	22.82	18.31
MnO	0.56	0.550	0.593	0.593	0.559	0.604	0.540
MgO	6.74	6.80	7.15	7.11	7.26	5.87	8.37
CaO	9.63	10.48	10.26	10.26	10.38	10.27	9.96
Na ₂ O	0.43	0.46	0.51	0.50	0.62	0.506 ⁺	0.49
K ₂ O	0.06	0.035	0.049	0.033	0.041	0.077	0.048
P ₂ O ₅	0.06	0.105	0.083	0.096	0.092	0.057	0.110
H ₂ O+	1.49						
H ₂ O-	0.37						
C	0.34						
Ni	<0.01						
Co	<0.01						
FeS	0.27						
Fe metal	<0.05						
TOTAL	99.77	100.424	99.807	99.911	101.101	101.947	100.405

Sources of data:

- 1 Olsen et al. (1978)
- 2 McCarthy (1971)
- 3 McCarthy et al. (1974)
- 4 Lovering (1975)
- 5 McCarthy et al. (1973)
- 6 Duke and Silver (1967)

n.d. - not determined.

⁺ - value supplied from Schmitt et al. (1972).

Contd/...

Table 4.7 continued

Meteorite	MOAMA	MOORE COUNTY	NUEVO LAREDO	PASA- MONTE	SERRA DE MAGÉ	SIOUX COUNTY	STANNERN
Source	4	5	6	2	2	2	2
SiO ₂	48.58	48.32	49.46	48.28	48.43	49.03	49.72
TiO ₂	0.22	0.438	0.95	0.724	0.167	0.617	0.979
Al ₂ O ₃	13.74	12.65	11.78	12.32	12.68	12.85	12.34
Cr ₂ O ₃	0.61	0.44	0.29	0.31	0.54	0.35	0.34
FeO*	14.85	17.24	20.10	19.21	16.18	18.58	17.78
MnO	0.50	0.520	0.56	0.566	0.550	0.558	0.524
MgO	11.89	9.41	5.46	6.57	11.36	7.11	6.98
CaO	9.47	9.37	10.40	10.30	9.08	10.37	10.66
Na ₂ O	0.22	0.414 ⁺	0.57	0.51	0.456 ⁺	0.44	0.62
K ₂ O	0.01	0.022	0.05	0.043	0.007	0.036	0.066
P ₂ O ₅	n.d.	0.036	0.11	0.108	0.057	0.069	0.103
H ₂ O+			0.14				
H ₂ O-			--				
C							
Ni							
Co							
FeS			0.21				
Fe metal							
TOTAL	100.09	98.860	100.08	98.941	99.507	100.010	100.112

Table 4.8. Published analyses of achondrites classified as howardites that are used to supplement the original data of the present investigation

Meteorite	BINDA	BUNUNU	CHAVES	FRANK- FORT (F)	FRANK- FORT (T)	MALVERN	MALVERN	YAMATO 7308	ZMENJ
Source	1	2	3	3	3	4	3	5	3
SiO ₂	50.29	48.67	51.79	50.87	50.89	49.25	49.16	51.06	50.06
TiO ₂	0.232	0.11	0.365	0.284	0.227	0.504	0.489	0.22	0.320
Al ₂ O ₃	6.97	8.87	6.84	5.44	4.27	10.07	9.96	3.64	6.48
Cr ₂ O ₃	0.75	0.56	0.61	1.01	1.11	n.d.	0.56	0.68	0.80
FeO*	16.83	16.04	15.33	17.37	17.89	18.14	18.04	16.00	17.22
MnO	0.540	0.53	0.479	0.551	0.560	0.52	0.531	0.57	0.523
MgO	17.76	14.20	18.39	19.28	20.94	11.81	12.40	22.02	17.26
CaO	5.58	6.77	5.64	4.59	3.64	8.23	8.06	3.50	5.44
Na ₂ O	0.20	0.34	0.22	0.20	0.22	n.d.	0.42	0.16	n.d.
K ₂ O	0.010	0.04	0.022	0.016	0.013	0.046	0.046	0.06	0.019
P ₂ O ₅	0.041	n.d.	0.057	0.046	0.034	0.078	0.089	0.01	0.046
H ₂ O+		1.53							
H ₂ O-		0.12							
Ni		0.06						0.012	
Co								0.007	
FeS		0.96						0.75	
Fe metal		1.01						0.39	
TOTAL	99.203	99.81	99.743	99.657	99.794	98.648	99.755	99.08	98.168

Sources of data: 1 McCarthy (1971); 2 Mason (1967); 3 McCarthy et al. (1972); 4 Von Michaelis (1969); 5 Yagi et al. (1978). n.d. - not determined. + - for explanation of Frankfort sample designations, see McCarthy et al. (1972).

Table 4.9. Published analyses of diogenites and mesosiderites used to supplement the original data of the present investigation

Meteorite	D I O G E N I T E S					MESOSIDERITES	
	ELLE-MEET	JOHNS-TOWN	SHALKA	TATA-HOUINE	YAMATO 6902	BAREA	DYARRL ISLAND
Source	1	1	1	1	2	3	3
SiO ₂	51.51	53.63	51.58	54.72	55.17	21.71	40.10
TiO ₂	0.057	0.120	0.062	0.068	0.072	0.11	0.77
Al ₂ O ₃	0.93	1.23	0.60	0.51	0.70	4.01	6.45
Cr ₂ O ₃	1.89	0.86	2.41	0.73	1.375	0.37	0.54
FeO*	17.34	16.26	16.27	15.14	12.58	5.61	14.61
MnO	0.567	0.500	0.553	0.496	0.515	0.24	0.48
MgO	27.01	25.90	25.78	28.24	26.22	6.62	10.88
CaO	0.80	1.46	0.73	0.76	1.21	2.54	5.39
Na ₂ O	0.11	0.03	0.04	0.03	0.0124	0.12	0.22
K ₂ O	0.003	0.002	0.002	0.000	0.0059	0.01	0.01
P ₂ O ₅	0.007	0.014	0.002	0.007	≤0.009	0.53	0.26
C						0.04	0.14
Ni						6.19	1.65
Co						0.12	0.08
FeS					1.339	1.62	2.32
Fe metal					0.667	50.24	15.76
TOTAL	100.224	100.006	98.029	100.701	99.875	100.08	99.66

Sources of data: 1 McCarthy et al. (1972)
 2 Shima (1974)
 3 Mason and Jarosewich (1973)

Table 4.10. Various published analyses from Tables 4.7 - 4.9 recalculated and normalized for comparison with the data of Tables 4.4 and 4.6

	ALLAN HILLS 7605	BAREA	BUNUNU	DYARRL ISLAND	NUEVO LAREDO	YAMATO 6902	YAMATO 7308
SiO ₂	50.28	51.85	50.63	50.31	49.59	56.37	52.14
TiO ₂	0.75	0.26	0.11	0.97	0.95	0.074	0.22
Al ₂ O ₃	12.56	9.58	9.23	8.09	11.81	0.72	3.72
Cr ₂ O ₃	0.40	0.88	0.58	0.68	0.29	1.405	0.69
FeO*	18.05	13.40	16.69	18.33	20.15	12.85	16.34
MnO	0.58	0.57	0.55	0.60	0.56	0.526	0.58
MgO	6.93	15.81	14.77	13.65	5.47	26.79	22.49
CaO	9.90	6.07	7.04	6.76	10.43	1.24	3.57
Na ₂ O	0.44	0.29	0.35	0.28	0.57	0.013	0.16
K ₂ O	0.06	0.02	0.04	0.01	0.05	0.006	0.06
P ₂ O ₅	0.06	1.27	n.d.	0.33	0.11	0.009	0.01
TOTAL	100.01	100.00	99.99	100.01	99.98	100.003	99.98

Table 4.11. Ranges present in the data of Tables 4.2, 4.4, and 4.7 - 4.10 inclusive

	EUCRITES	HOWARDITES	DIOGENITES	MESOSIDERITES
SiO_2	48.26 -50.28	49.16 -52.14	51.51 -56.37	50.31 -54.38
TiO_2	0.167- 0.979	0.11 - 0.534	0.057- 0.120	0.231- 0.97
Al_2O_3	11.55 -13.74	3.72 -10.78	0.51 - 1.23	7.50 -12.23
Cr_2O_3	0.29 - 0.61	0.56 - 1.11	0.73 - 2.41	0.678- 1.652
FeO^*	14.85 -22.82	15.33 -18.14	12.85 -17.34	7.86 -18.33
MnO	0.50 - 0.604	0.479- 0.58	0.496- 0.567	0.493- 0.621
MgO	5.47 -11.89	11.16 -22.49	25.78 -28.24	12.84 -20.48
CaO	9.08 -10.66	3.57 - 8.60	0.73 - 1.46	5.93 - 9.39
Na_2O	0.22 - 0.62	0.15 - 0.42	0.013- 0.11	0.18 - 0.39
K_2O	0.007- 0.077	0.009- 0.06	0.000- 0.006	0.000- 0.02
P_2O_5	0.036- 0.110	0.01 - 0.089	0.002- 0.014	0.33 - 2.280

4.6 NORMATIVE COMPOSITIONS

CIPW norms were calculated by computer for all the bulk chemical analyses used in this investigation, the recalculated forms of the analyses being used wherever available. These norms are listed in full on microfiche as Appendix 4, but are presented in an abbreviated form in this chapter. Tables 4.12 and 4.13 set out the normative compositions of the achondrites and mesosiderites analyzed in the present study, while those of the analyses taken from the literature are given in Tables 4.14 - 4.16. The norms are quoted in terms both of weight % and cation %, and the proportions of salic and femic normative minerals are included in the tabulation.

4.7 DISCUSSION

Although the interpretation of the inter-relationships of the meteorites for which compositional and normative data are given here is considered in detail in the following chapter, some preliminary observations may be made at this stage.

4.7.1 The analyses of Malvern and Binda

Four analyses of the howardite Malvern have been made at various times in this Department. The new analyses are listed in Table 4.2, the earlier in Table 4.8. Agreement throughout is good, the variations presumably reflecting the difficulty of representative sampling of a very heterogeneous meteorite breccia. This difficulty is well illustrated by the two new analyses. Despite having sampled large areas of the meteorite, Malvern (UCT) and Malvern (BLM) are by no means identical, but show slight differences in Si, Al, Mg, Ca, and P in particular. The two analyses of Binda carried out at UCT are in good agreement (Tables 4.2 and 4.8). Normalization of the earlier analysis to 100% makes it almost identical to that

Table 4.12. CIPW norms, expressed both as cation % and weight %, calculated for the achondrite analyses of Table 4.2

	MALVERN (UCT)			MALVERN (BLM)			BINDA			KAPOETA			MOLTENO		
	Cation %	Wt %	Cation %	Cation %	Wt %	Cation %	Cation %	Wt %	Cation %	Cation %	Wt %	Cation %	Cation %	Wt %	
Qz	1.01	1.07	0.76	0.80								0.20	0.21		
Z	0.00	0.01	0.00	0.01						0.00	0.01				
Or	0.24	0.24	0.27	0.26				0.05		0.07	0.07		0.10	0.10	
Pl	29.77	28.88	31.58	30.56			0.05	20.13		24.10	23.75		26.54	25.97	
(Ab)	2.95	2.71	2.95	2.71			1.35	1.27		2.71	2.54		2.74	2.54	
(An)	26.83	26.17	28.62	27.85			18.94	18.86		21.38	21.21		23.81	23.43	
Di	11.57	11.70	11.82	11.95			7.04	7.17		8.99	9.13		10.22	10.35	
(Wo)	5.78	5.89	5.91	6.00			3.52	3.66		4.49	4.65		5.11	5.25	
(En)	3.17	2.79	3.12	2.74			2.31	2.07		2.88	2.58		3.07	2.72	
(Fs)	2.62	3.03	2.79	3.21			1.21	1.43		1.61	1.90		2.04	2.38	
Hy	55.89	56.17	54.01	54.43			69.31	69.01		65.00	64.74		61.42	61.37	
(En)	30.60	26.93	28.54	25.05			45.45	40.84		41.64	37.27		36.90	32.77	
(Fs)	25.29	29.25	25.47	29.37			23.85	28.16		23.36	27.47		24.52	28.61	
Ol							2.08	2.02		0.33	0.32				
(Fo)							1.37	1.15		0.21	0.17				
(Fa)							0.72	0.87		0.12	0.14				
Cm	0.66	0.86	0.64	0.84			0.84	1.12		0.88	1.17		0.78	1.02	
Il	0.73	0.97	0.76	1.01			0.33	0.45		0.55	0.74		0.64	0.85	
Ap	0.13	0.14	0.15	0.17			0.05	0.06		0.10	0.11		0.11	0.12	
SALIC	31.03	30.19	32.61	31.62			20.35	20.19		24.17	23.82		26.85	26.28	
FEMIC	68.97	69.84	67.39	68.40			79.65	79.82		75.83	76.21		73.15	73.73	
TOTAL	100.00	100.02	100.00	100.03			100.00	100.01		100.00	100.03		100.00	100.01	

Table 4.13. CIPW norms, expressed both as cation % and weight %, calculated for the mesosiderite analyses of Table 4.4

	MINCY		PATWAR		ESTHERVILLE		MOUNT PADBURY	
	Cation %	Wt %	Cation %	Wt %	Cation %	Wt %	Cation %	Wt %
Qz	5.20	5.71	2.98	3.19	1.93	2.10	6.15	6.72
Or	0.05	0.05			0.02	0.02	0.02	0.02
Pl	21.18	21.43	23.21	22.95	27.67	27.64	22.95	23.11
(Ab)	2.21	2.12	2.17	2.03	2.77	2.62	1.60	1.52
(An)	18.98	19.32	21.04	20.92	24.90	25.01	21.35	21.58
Di	0.80	0.81	3.55	3.60	5.92	6.03	5.44	5.52
(Wo)	0.40	0.42	1.78	1.84	2.96	3.11	2.72	2.87
(En)	0.33	0.30	1.18	1.06	2.13	1.93	2.10	1.92
(Fs)	0.07	0.09	0.59	0.70	0.83	0.99	0.61	0.74
Hy	67.72	65.80	66.79	66.18	61.87	61.01	62.87	61.40
(En)	55.22	50.71	44.50	39.91	44.53	40.36	48.67	44.38
(Fs)	12.50	15.09	22.29	26.27	17.34	20.66	14.20	17.02
Cm	1.78	2.43	0.75	1.00	0.98	1.32	1.15	1.56
Il	0.40	0.56	0.32	0.44	0.42	0.58	0.40	0.55
Ap	2.86	3.30	2.41	2.71	1.17	1.34	1.02	1.17
SALIC	26.43	27.20	26.18	26.14	29.62	29.75	29.13	29.85
FEMIC	73.57	72.90	73.82	73.93	70.38	70.28	70.87	70.19
TOTAL	100.00	100.10	100.00	100.07	100.00	100.03	100.00	100.04

Contd/...

Table 4.13 continued

	VACA MUERTA		EMERY		ŁOWICZ	
	Cation %	Wt %	Cation %	Wt %	Cation %	Wt %
Qz	5.18	5.52	10.85	11.67	8.83	9.57
Or	0.08	0.08	0.09	0.09	0.11	0.11
Pl	28.71	28.19	35.22	34.87	32.28	32.23
(Ab)	2.55	2.37	3.52	3.30	2.95	2.79
(An)	26.17	25.82	31.71	31.57	29.33	29.44
Di	0.16	0.16	0.11	0.11	2.97	2.99
(Wo)	0.08	0.08	0.06	0.06	1.48	1.55
(En)	0.05	0.05	0.04	0.04	1.14	1.04
(Fs)	0.03	0.03	0.01	0.02	0.34	0.40
Hy	59.89	59.12	47.46	45.99	51.44	49.91
(En)	39.19	34.90	35.55	31.94	39.73	35.97
(Fs)	20.70	24.22	11.90	14.05	11.72	13.94
Cm	1.40	1.85	0.93	1.24	0.90	1.21
Il	0.42	0.57	0.55	0.74	0.51	0.70
Ap	4.15	4.64	4.79	5.40	2.96	3.37
SALIC	33.98	33.80	46.17	46.64	41.22	41.91
FEMIC	66.02	66.33	53.83	53.49	58.78	58.18
TOTAL	100.00	100.13	100.00	100.13	100.00	100.09

Table 4.14. CIPW norms, expressed both as cation % and weight %, calculated for the published analyses of eucrites listed in Table 4.7

	ALLAN HILLS 7605			BÉRÉBA			CACHARI			HARAIYA			JUVINAS			LAKANGAON			MACIBINI		
	Cation %	Wt %		Cation %	Wt %		Cation %	Wt %		Cation %	Wt %		Cation %	Wt %		Cation %	Wt %		Cation %	Wt %	
Qz	4.68	4.84		2.21	2.29		0.62	0.64		1.23	1.27		1.08	1.13		0.98	1.02		1.53	1.60	
Z				0.01	0.01		0.01	0.01		0.00	0.01		0.01	0.01					0.01	0.01	
Or	0.37	0.35		0.22	0.21		0.30	0.29		0.20	0.20		0.25	0.24		0.47	0.46		0.29	0.28	
Pl	37.64	35.84		38.24	36.51		38.86	36.94		37.84	35.97		39.25	37.81		34.84	33.30		36.27	34.85	
(Ab)	4.12	3.72		4.30	3.89		4.78	4.32		4.69	4.23		5.73	5.25		4.72	4.28		4.55	4.15	
(An)	33.52	32.12		33.95	32.62		34.08	32.63		33.15	31.74		33.52	32.57		30.13	29.02		31.72	30.70	
Di	13.86	14.03		15.58	15.86		14.84	15.03		15.51	15.72		15.11	15.52		17.91	18.45		14.90	15.15	
(Wo)	6.93	6.93		7.79	7.82		7.42	7.42		7.76	7.75		7.56	7.66		8.95	9.00		7.45	7.53	
(En)	2.84	2.46		3.05	2.64		2.98	2.58		3.08	2.66		3.10	2.71		2.84	2.47		3.37	2.95	
(Fs)	4.09	4.65		4.74	5.40		4.44	5.04		4.67	5.30		4.46	5.14		6.11	6.98		4.07	4.67	
Hy	41.77	42.80		42.13	43.51		43.90	45.05		43.82	45.01		42.80	44.48		44.09	46.52		45.26	46.30	
(En)	17.12	14.80		16.49	14.29		17.63	15.23		17.42	15.04		17.53	15.37		13.98	12.15		20.50	17.90	
(Fs)	24.64	27.99		25.64	29.22		26.27	29.81		26.40	29.97		25.27	29.11		30.10	34.37		24.76	28.40	
Ol																					
(Fo)																					
(Fa)																					
Cm	0.46	0.59		0.37	0.47		0.37	0.47		0.37	0.47		0.38	0.50		0.36	0.47		0.43	0.62	
Il	1.09	1.42		1.02	1.34		0.92	1.20		0.81	1.06		0.92	1.21		1.22	1.61		1.03	1.36	
Ap	0.13	0.14		0.23	0.25		0.18	0.20		0.21	0.23		0.20	0.22		0.12	0.14		0.24	0.26	
SALIC	42.69	41.03		40.67	39.02		39.79	37.88		39.28	37.45		40.58	39.20		36.29	34.77		38.10	36.74	
FEMIC	57.31	58.99		59.33	61.43		60.21	61.95		60.72	62.49		59.42	61.93		63.71	67.19		61.90	63.69	
TOTAL	100.00	100.02		100.00	100.45		100.00	99.83		100.00	99.93		100.00	101.12		100.00	101.96		100.00	100.43	

Contd/...

Table 4.14 continued

MOAMA			MOORE COUNTY			NUEVO LAREDO			PASAMONTE			SERRA DE MAGÉ			SIOUX COUNTY			STANNERN		
Cation %	Wt %		Cation %	Wt %		Cation %	Wt %		Cation %	Wt %		Cation %	Wt %		Cation %	Wt %		Cation %	Wt %	
Qz				2.35	2.42	3.95	4.04	1.81	1.85						2.11	2.18	2.98	3.10		
Z								0.01	0.01						0.01	0.01	0.01	0.02		
Or	0.06	0.06	0.14	36.16	0.13	0.31	0.30	0.27	0.25			0.04			0.22	0.21	0.41	0.39		
Pl	38.96	38.34	36.16	34.45	34.45	36.54	34.34	37.84	35.52			36.39	36.70		38.49	36.70	37.72	35.94		
(Ab)	2.00	1.86	0.00	0.00	0.00	5.40	4.82	4.84	4.32			3.86	3.72		4.12	3.72	5.79	5.25		
(An)	36.96	36.47	36.16	34.45	34.45	31.14	29.52	33.00	31.20			32.53	32.98		34.38	32.98	31.93	30.69		
Di	8.52	8.67	9.93	9.88	9.88	18.15	18.37	16.26	16.31			10.08	15.26		15.05	15.26	17.94	18.20		
(Wo)	4.26	4.39	4.96	4.94	4.94	9.07	8.98	8.13	8.03			5.08	7.53		7.52	7.53	8.97	9.00		
(En)	2.50	2.23	2.45	2.11	2.11	3.00	2.57	3.10	2.65			2.43	2.65		3.07	2.65	3.76	3.26		
(Fs)	1.76	2.05	2.51	2.84	2.84	6.07	6.83	5.03	5.64			2.57	5.07		4.46	5.07	5.21	5.94		
Hy	48.89	49.16	50.20	50.01	50.01	39.08	40.45	42.15	42.94			47.50	43.82		42.68	43.82	38.90	39.90		
(En)	28.73	25.58	24.81	21.33	21.33	12.93	11.06	16.08	13.72			23.06	15.05		17.39	15.05	16.29	14.13		
(Fs)	20.16	23.59	25.39	28.68	28.68	26.16	29.40	26.07	29.22			24.44	28.76		25.29	28.76	22.61	25.77		
Ol	2.59	2.55										4.31	4.26							
(Fo)	1.52	1.27										2.39	1.97							
(Fa)	1.07	1.29										1.93	2.30							
Cm	0.68	0.90	0.51	0.65	0.65	0.34	0.43	0.36	0.46			0.80	0.52		0.40	0.52	0.39	0.50		
Il	0.31	0.42	0.64	0.83	0.83	1.40	1.80	1.07	1.38			0.32	1.17		0.90	1.17	1.42	1.86		
Ap			0.08	0.09	0.09	0.24	0.26	0.24	0.26			0.12	0.16		0.15	0.16	0.22	0.24		
SALIC	39.02	38.39	38.65	37.00	37.00	40.79	38.68	39.92	37.63			36.43	39.11		40.83	39.11	41.12	39.44		
FEMIC	60.98	61.70	61.35	61.46	61.46	59.21	61.32	60.08	61.34			63.09	60.93		59.17	60.93	58.88	60.70		
TOTAL	100.00	100.10	100.00	98.46	98.46	100.00	99.99	100.00	98.97			99.52	100.03		100.00	100.03	100.00	100.14		

Table 4.15. CIPW norms, expressed both as cation % and weight %, calculated for the published analyses of howardites listed in Table 4.8

	BINDA		BUNUNU		CHAVES	
	Cation %	Wt %	Cation %	Wt %	Cation %	Wt %
Qz					0.49	0.53
Z					0.00	0.01
Or	10.06	0.06	0.24	0.24	0.13	0.13
Pl	20.13	19.78	26.94	26.46	19.62	19.47
(Ab)	1.82	1.69	3.18	2.96	1.98	1.86
(An)	18.31	18.09	23.77	23.50	17.64	17.61
Di	7.56	7.63	9.25	9.40	8.02	8.15
(Wo)	3.78	3.90	4.62	4.77	4.01	4.18
(En)	2.47	2.20	2.82	2.51	2.74	2.47
(Fs)	1.31	1.54	1.81	2.12	1.27	1.50
Hy	67.42	66.64	61.92	62.00	70.43	69.74
(En)	44.03	39.25	37.73	33.66	48.11	48.33
(Fs)	23.39	27.40	24.19	28.35	22.31	26.40
Ol	3.59	3.45	0.85	0.83		
(Fo)	2.34	1.95	0.52	0.43		
(Fa)	1.24	1.50	0.33	0.40		
Cm	0.83	1.10	0.64	0.85	0.67	0.90
Il	0.33	0.44	0.15	0.21	0.51	0.69
Ap	0.09	0.10			0.12	0.14
SALIC	20.19	19.85	27.18	26.69	20.25	20.14
FEMIC	79.81	79.37	72.82	73.30	79.75	79.62
TOTAL	100.00	99.22	100.00	100.00	100.00	99.76

Contd/...

Table 4.15 continued

	FRANKFORT (F)		FRANKFORT (T)		MALVERN	
	Cation %	Wt %	Cation %	Wt %	Cation %	Wt %
Qz					1.56	1.62
Z					0.01	0.01
Or	0.10	0.09	0.08	0.08	0.28	0.27
Pl	15.78	15.59	12.60	12.49	28.48	27.34
(Ab)	1.81	1.69	1.97	1.86	0.00	0.00
(An)	13.98	13.90	10.62	10.63	28.48	27.34
Di	6.91	7.01	5.78	5.88	10.83	10.80
(Wo)	3.45	3.58	2.89	3.01	5.42	5.43
(En)	2.30	2.06	1.96	1.77	2.90	2.51
(Fs)	1.15	1.36	0.93	1.10	2.51	2.86
Hy	71.89	71.26	72.64	72.17	57.93	57.48
(En)	47.91	42.99	49.25	44.43	31.06	26.90
(Fs)	23.98	28.27	23.39	27.74	26.88	30.59
Ol	3.72	3.58	7.30	7.04		
(Fo)	2.48	2.08	4.95	4.17		
(Fa)	1.24	1.51	2.35	2.87		
Cm	1.12	1.49	1.22	1.63		
Il	0.40	0.54	0.32	0.43	0.73	0.96
Ap	0.10	0.11	0.07	0.08	0.17	0.18
SALIC	15.88	15.69	12.68	12.57	30.33	29.24
FEMIC	84.12	83.98	87.32	87.24	69.67	69.43
TOTAL	100.00	99.67	100.00	99.81	100.00	98.67

Table 4.15 continued

	MALVERN		YAMATO 7308		ZMENJ	
	Cation %	Wt %	Cation %	Wt %	Cation %	Wt %
Qz					0.38	0.40
Z	0.00	0.01				
Or	0.28	0.27	0.35	0.35	0.12	0.11
Pl	29.66	28.71	10.58	10.61	18.12	17.63
(Ab)	3.87	3.55	1.42	1.35	0.00	0.00
(An)	25.79	25.16	9.16	9.25	18.12	17.63
Di	11.71	11.83	6.64	6.81	7.45	7.42
(Wo)	5.85	5.96	3.32	3.50	3.73	3.78
(En)	3.24	2.85	2.36	2.15	2.40	2.10
(Fs)	2.62	3.03	0.96	1.16	1.33	1.53
Hy	54.44	54.63	75.67	75.28	72.47	70.72
(En)	30.10	26.48	53.69	48.95	46.59	40.88
(Fs)	24.34	28.15	21.97	26.33	25.87	29.84
Ol	2.39	2.36	5.69	5.48		
(Fo)	1.32	1.09	4.04	3.44		
(Fa)	1.07	1.27	1.65	2.04		
Cm	0.63	0.82	0.75	1.02	0.90	1.18
Il	0.70	0.93	0.30	0.42	0.46	0.61
Ap	0.19	0.21	0.02	0.02	0.10	0.11
SALIC	29.94	28.99	10.93	10.96	18.62	18.14
FEMIC	70.06	70.79	89.07	89.02	81.38	80.04
TOTAL	100.00	99.78	100.00	99.99	100.00	98.18

Table 4.16. GIPW norms, expressed both as cation % and weight %, calculated for the published analyses of diogenites and mesosiderites listed in Table 4.9

D I O G E N I T E S								
	ELLEMEET		JOHNSTOWN		SHALKA		TATAHOINE	
	Cation %	Wt %	Cation %	Wt %	Cation %	Wt %	Cation %	Wt %
Qz								
Co								
Or	0.02	0.02	0.01	0.01	0.01	0.01		
Pl	2.95	2.97	3.42	3.47	1.82	1.79	1.47	1.51
(Ab)	0.97	0.93	0.26	0.25	0.36	0.34	0.26	0.25
(An)	1.99	2.03	3.15	3.22	1.46	1.45	1.21	1.26
Di	1.48	1.53	3.09	3.18	1.73	1.74	1.90	1.99
(Wo)	0.74	0.79	1.54	1.64	0.87	0.90	0.95	1.03
(En)	0.55	0.50	1.14	1.05	0.65	0.58	0.73	0.68
(Fs)	0.19	0.23	0.40	0.49	0.22	0.26	0.22	0.27
Hy	80.18	80.06	89.68	89.24	90.20	87.55	92.09	92.46
(En)	59.28	54.71	66.32	61.01	67.30	60.50	70.69	66.15
(Fs)	20.90	25.34	23.35	28.23	22.90	27.05	21.40	26.31
Ol	13.25	12.76	2.69	2.58	3.50	3.27	3.65	3.53
(Fo)	9.80	8.45	1.99	1.71	2.61	2.19	2.81	2.45
(Fa)	3.45	4.31	0.70	0.87	0.89	1.08	0.85	1.08
Cm	2.03	2.78	0.93	1.27	2.66	3.55	0.77	1.08
Il	0.08	0.11	0.16	0.23	0.09	0.12	0.09	0.13
Ap	0.01	0.02	0.03	0.03			0.01	0.02
SALIC	2.97	2.98	3.43	3.48	1.83	1.80	1.47	1.51
FEMIC	97.03	97.25	96.57	96.53	98.17	96.23	98.53	99.20
TOTAL	100.00	100.23	100.00	100.01	100.00	98.04	100.00	100.71

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Table 4.16 continued

	DIOGENITES		MESOSIDERITES			
	YAMATO 6902		BAREA		DYARRL ISLAND	
	Cation %	Wt %	Cation %	Wt %	Cation %	Wt %
Qz	3.64	4.04	5.54	5.95	2.08	2.19
Co			1.19	1.09		
Or	0.03	0.04	0.12	0.12	0.06	0.06
Pl	1.95	2.00	24.54	24.27	23.88	23.16
(Ab)	0.11	0.11	2.62	2.45	2.58	2.37
(An)	1.84	1.89	21.92	21.82	21.30	20.79
Di	3.28	3.37			8.68	8.75
(Wo)	1.64	1.76			4.34	4.42
(En)	1.29	1.20			2.51	2.21
(Fs)	0.34	0.42			1.83	2.12
Hy	89.48	88.34	64.61	63.85	62.44	62.25
(En)	70.73	65.52	43.86	39.38	36.11	31.79
(Fs)	18.74	22.82	20.75	24.47	26.33	30.46
Ol						
(Fo)						
(Fa)						
Cm	1.50	2.07	0.97	1.30	0.77	1.00
Il	0.10	0.14	0.36	0.49	1.38	1.84
Ap	0.02	0.02	2.67	3.01	0.71	0.78
SALIC	5.63	6.07	31.39	31.43	26.02	25.41
FEMIC	94.37	93.94	68.61	68.65	73.98	74.63
TOTAL	100.00	100.01	100.00	100.07	100.00	100.03

produced in the present investigation, as is demonstrated by the inter-element plots in Chap. 5.

4.7.2 Compositional differences between howardites and mesosiderites

Comparison of the recalculated data of Tables 4.2 and 4.4 shows that both howardites and mesosiderites are compositionally variable, as indicated by previous work (PRIOR, 1918, 1920; POWELL, 1971; MASON and JAROSEWICH, 1973). To appreciate the full compositional range of the howardites, the supplementary data of Table 4.8 must be taken into consideration. Then some generalizations can be made about the differences between the two types of meteorites (see Table 4.11). The silicate fractions of the mesosiderites appear, in general, to contain more Si, Al, Cr, Ca, and P than the howardites, which are, however, considerably richer in Fe and slightly richer in Ti and K. Trace elements in the mesosiderites are depleted in varying degrees with respect to howardites, with the exception of V, which is in sympathetic relationship to Cr. It is interesting to note that Binda exhibits trace element concentrations more typical of the 'silicate' portions of the mesosiderites than of the howardites.

4.7.3 The check analyses of Vaca Muerta and Łowicz

Comparison of the analyses of Vaca Muerta and Łowicz made during the present study (Table 4.3) and the check analyses in their original form (Table 4.5) shows close agreement between the work of the three analysts involved, despite the different techniques employed. The correspondence becomes even closer when the analyses of Vaca Muerta and Łowicz carried out by the writer and by E. Jarosewich are expressed in the same form (Table A9.2 and Cols 1 and 3 of Table 4.6). When these analyses are normalized to 100% (Table 4.4 and Cols 2 and 4 of Table 4.6), the agreement becomes very

Table 4.17. Ca/Al ratios calculated from the original and the check analyses of Vaca Muerta and Łowicz

ANALYST	Ca/Al ratio (wt)	
	VACA MUERTA	ŁOWICZ
Jarosewich	1.09	1.03
Rhodes	1.05	1.03
Simpson	1.06	1.02

good, showing that initial differences in SiO_2 were merely apparent. This correspondence dispels any doubt that may have existed about the validity of Ca/Al ratios derived from the analyses of mesosiderites performed during the present investigation. A comparison of the Ca/Al ratios calculated from the original and the check analyses is presented in Table 4.17.

4.7.4 Normative compositions

Although almost all the meteorites included in this investigation are breccias, many of them polymict in character, calculation of their CIPW norms was considered worthwhile on the assumption that their bulk chemical compositions represent a rough average of the materials present in the source areas from which they were derived. This concept, which is discussed at greater length later in this report, assumes also that components exotic to the source region of a particular meteorite are present, if at all, in only minor proportions. If these assumptions are valid, the normative mineralogical compositions even of polymict breccias provide a basis for comparison of the materials from which these brecciated meteorites originated. This is particularly important for meteorites with glassy constituents because their modal compositions cannot easily be compared.

Inspection of the normative data presented in Tables 4.12 - 4.16 leads to the following observations:

(a) Howardites (Tables 4.12 and 4.15)

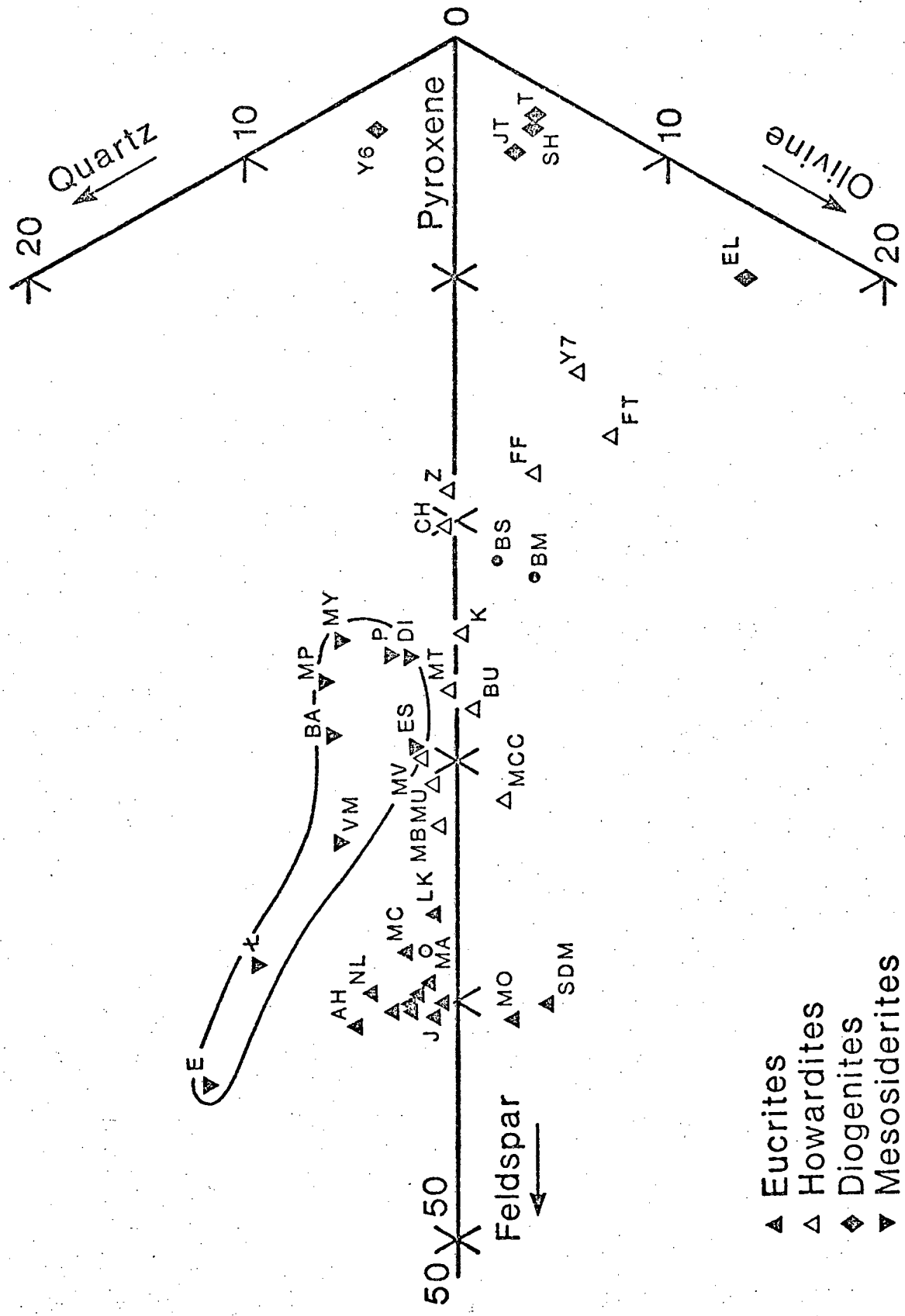
On a double ternary plot of normative quartz, feldspar, pyroxene, and olivine (Fig. 4.1), the howardites included in the present investigation define a trend that crosses the boundary between quartz-normative and olivine-normative fields at a low angle. Only Frankfort (T) (McCARTHY et al., 1972) and Yamato 7308 (YAGI et al., 1978) exhibit normative olivine in excess of 5% on the plot. The range of bulk chemical compositions in the howardite class is reflected in this trend and also in the variability of the contents of normative plagioclase, diopside, and hypersthene in the members of the class (Table 4.18). The norms of the various analyses of Malvern show good agreement, but the sample analyzed by McCARTHY et al. (1972) plots in the olivine-normative field, whereas the other three are quartz-normative. Agreement between the norms of the samples of Binda is close, both being olivine-normative.

(b) Mesosiderites (Tables 4.13 and 4.16)

Fig. 4.1 shows that the mesosiderites lie along a trend roughly parallel to that of the howardites but displaced from it and extending it farther into the quartz-normative field. As in the howardites, normative plagioclase and pyroxene vary appreciably in amount from meteorite to meteorite. As might be expected from Fig. 4.1 and the element concentration ranges noted in howardites and mesosiderites, the ranges present in the normative mineralogy of mesosiderites do not coincide with those of howardites (Table 4.18). The norm of Barea (Table 4.16) is unusual in containing corundum, which indicates an excess of Al in the calculation procedure (BARTH, 1962). This excess arises from much of the Ca having been allocated to the calculation of normative apatite. Consequently, inadequate Ca was

Fig. 4.1. A portion of the double ternary plot of normative quartz, feldspar, pyroxene, and olivine. The achondrites and mesosiderites studied are plotted from the data (cation %) of Tables 4.12 - 4.16. The mesosiderite field is outlined. Note that Binda and Macibini are accorded special symbols because of doubt over their classification (SIMPSON and AHRENS, 1979; and this work). The abbreviations used to identify individual meteorites in this figure (and all others throughout this work) are explained in Table 1.3.

AB



- ▲ Euclrites
- △ Howardites
- ◆ Diogenites
- ▼ Mesosiderites

Table 4.18. A comparison of the ranges, in cation %, of the main normative minerals of the achondrites and the mesosiderites (data from Tables 4.12 - 4.16)

	EUCRITES	HOWARDITES	DIOGENITES	MESOSIDERITES
Qz	0.0 - 4.68	0.0 - 1.56	0.0 - 3.64	1.93-10.85
Pl	34.84-39.25	10.58-31.58	1.47- 3.42	21.18-35.22
(Ab)	0.0 - 5.79	0.0 - 3.87	0.11- 0.97	1.60- 3.52
(An)	30.13-36.96	9.16-28.62	1.21- 3.15	18.98-31.71
Di	8.52-18.15	5.78-11.82	1.48- 3.28	0.0 - 8.68
(Wo)	4.26- 9.07	2.89- 5.91	0.74- 1.64	0.0 - 4.34
(En)	2.45- 3.76	1.96- 3.24	0.55- 1.29	0.0 - 2.51
(Fs)	1.76- 6.11	0.93- 2.79	0.19- 0.40	0.0 - 1.83
Hy	38.90-50.20	54.01-75.67	80.18-92.09	47.46-67.72
(En)	12.93-28.73	28.54-53.69	59.28-70.73	35.55-55.22
(Fs)	20.16-30.10	21.97-26.88	18.74-23.35	11.72-26.33
Ol	0.0 - 4.31	0.0 - 7.30	2.69-13.25	---
(Fo)	0.0 - 2.39	0.0 - 4.95	1.99 - 9.80	---
(Fa)	0.0 - 1.93	0.0 - 2.35	0.70 - 3.45	---

Table 4.19. Trace element data available in the literature for the achondrites whose major element compositions appear in Tables 4.7 and 4.8

	Ba (ppm)	Sr (ppm)	Zr (ppm)	Y (ppm)
<u>Table 4.7</u>				
Béréba	33	81	52	17
Cachari	48	84	45	15
Haraiya	25	74	36	14
Juvinas	31	78	46	16
Macibini	36	77	54	18
Moore County	18.6 ¹	63.9 ¹	16 ²	--
Nuevo Laredo	39.3 ¹	84.4 ³	67 ²	--
Pasamonte	33	80	53	17
Serra de Magé	7.6 ⁴	51 ⁵	14 ⁶	--
Sioux County	28	76	42	14
Stannern	50	92	87	26
<u>Table 4.8</u>				
Binda	11	33	15	4.4
Chaves	17	40	28	8.4
Frankfort (F)	11	30	19	6.5
Frankfort (T)	8	24	14	4.6
Malvern	--	58 ⁷	42 ⁷	--
Malvern	22	59	36	12
Zmenj	9.3 ⁸	--	--	--

Sources of data: All data from McCarthy et al. (1972, 1973) except -

1 Tera <u>et al.</u> (1970)	5 Philpotts and Schnetzler (1970)
2 Schmitt <u>et al.</u> (1964a)	6 Palme <u>et al.</u> (1978)
3 Gast (1965)	7 Von Michaelis <u>et al.</u> (1969)
4 Schnetzler and Philpotts (1968)	8 Fukuoka <u>et al.</u> (1977)

left for the 'formation' of anorthite, and none for wollastonite. The presence of normative corundum, coupled with the low Ca/Al ratio (0.85) of the meteorite (MASON and JAROSEWICH, 1973), suggests that the analysis of Barea may be deficient in Ca. The norms of Mincy, Vaca Muerta, and Emery all show low contents of wollastonite (Table 4.13) and therefore tend towards being corundum-normative, but these meteorites have Ca/Al ratios typical of the mesosiderites investigated - 1.07, 1.06, and 1.04 respectively.

(c) Eucrites (Table 4.14)

The eucrites studied all plot in a restricted area just within the quartz-normative field (Fig. 4.1) with the exception of Moama and Serra de Magé, both of which are generally regarded as cumulates. This area becomes very small if the remaining cumulate, Moore County, and the unusually Fe-rich eucrites Nuevo Laredo and Lakangaon, are excluded. Similarly, exclusion of the data relating to these meteorites from Table 4.18 would curtail the compositional ranges of the main normative minerals recorded for the eucrites. Even with the inclusion of these 'special' eucrites, the ranges shown in Table 4.18 for the class are much narrower than those of the howardites and mesosiderites.

(d) Diogenites (Table 4.16)

The diogenites are all olivine-normative except Yamato 6902, which has considerably more SiO_2 in its analysis than the other diogenites (Tables 4.9 and 4.10). Ellemeet is the most highly olivine-normative meteorite studied. The remaining three diogenites plot in a cluster that lies roughly on the extension of a trend that includes the eucrites and most of the howardites (Fig. 4.1). Interesting to note is the variability of normative chromite in the diogenites (Table 4.16) and the almost continuous sequence of compositions in hypersthene, the main Mg-bearing normative

mineral in the achondrites, that extends from eucrites through howardites to diogenites without major breaks or overlaps (Table 4.18).

4.7.5 Comparison of the modal and normative data on four achondrites

The volumetric modal measurements made on Binda, Bununu, Malvern, and Molteno (Tables 3.1 and 3.2) are re-expressed on a weight basis in Table 3.3, as explained in the accompanying text in Chap. 3. This was, in effect, an attempt to reconstruct the original mineralogical compositions of these achondrites - or, alternatively, to estimate the mineral proportions present in the source areas from which these brecciated meteorites were derived. The assumptions made in order to produce the data of Table 3.3 are specified in Chap. 3. They appear to be largely justified, as is shown by comparison of the weight modes with the weight norms of the four achondrites (Tables 4.12 and 4.15). Agreement is within about 5% relative for the most abundant constituent of these meteorites, the total pyroxene content, except for Binda, in which the error is about 15%. The values for plagioclase in Malvern are likewise within 5%, but agreement is poorer (about 30%) in the other achondrites. Opaque minerals appear to have been grossly over-estimated in the modes, and therefore show little correspondence with the weight normative values because of accentuation of the errors by the high specific gravities of the opaque phases. The closest agreement exists between the mode and the norm of Malvern, and may be attributable to the higher quality of the modal data available for that meteorite.

CHAPTER 5

INTER-ELEMENT RELATIONSHIPS IN THE ACHONDRITES AND MESOSIDERITES INVESTIGATED

There is no science without fancy,
and no art without facts.

Vladimir Nabokov (1899-)

5.1 INTRODUCTION

The preceding chapter presented bulk compositional data, some new, some taken from the literature, on 42 achondrites and mesosiderites. This chapter will make use of these data to examine the inter-element relationships in eucrites, howardites, diogenites, and the silicate fractions of mesosiderites in an attempt to advance our understanding of the processes that have operated in the formation of these classes of meteorites. Furthermore, it may be possible, from a study of the relationships between these various types of meteorites, to formulate some conclusions - albeit tentatively - on whether they all originated from the same parent body. The data are used also to review critically the present classification of the meteorites Binda and Macibini, and subsequently for an examination - necessarily brief because the available data are inadequate for a solution - of the problems of classification of the achondrites, problems that have recently been accentuated by the discovery of new varieties of eucritic and diogenitic meteorites in the Antarctic.

Some preliminary interpretation of the bulk compositional data was made in the preceding chapter (section 4.7). Compositional differences between howardites and the silicate portions of mesosiderites were noted in

the concentration ranges presented in Table 4.11, and these differences are reflected also in the ranges in normative mineralogy present in these meteorite classes (Table 4.18 and Fig. 4.1). In this chapter, the interpretation will be carried further, using graphical methods to study inter-element relationships that may reveal the petrogenetic history of the source rocks from which the brecciated achondrites and mesosiderites were formed.

5.2 RELATIONSHIPS BETWEEN REFRACTORY ELEMENTS

5.2.1 Introduction

The refractory elements are those, according to GROSSMAN and LARIMER (1974), that condense from a gas of solar composition with a total pressure of 10^{-4} atm at temperatures above 1250°K . Studies of their abundance in stony meteorites (AHRENS, 1970a, 1970c) showed a trend of enrichment from chondrites through the basaltic achondrites, with eucrites displaying greater enrichment than howardites. The stony meteorites with the highest concentrations of refractory elements are Stannern and Nuevo Laredo, and the trend extends to Apollo 11 fines (AHRENS, 1970c). Previous work, and the data presented in Tables 4.1-4.4, have shown that the achondrites and mesosiderites included in this investigation are, relative to chondrites, strongly depleted in volatile elements (those condensing from the solar nebula at temperatures lower than 1250°K). The concentrations of some volatiles, e.g. Rb, are generally below the detection limit of the analytical technique employed (XRF). In the present study, to determine these elements with some degree of precision would have called for unjustifiably long counting times using XRF spectrometry. Accordingly, in the examination of inter-element relationships in this chapter, emphasis falls on the refractory elements. Some of these relationships have been studied previously by other members of this Department (e.g. AHRENS and VON MICHAELIS, 1969b) but are here

re-examined using new data that have been recalculated and normalized to make them as closely comparable as possible. Furthermore, the re-examination was carried out with the following specific objectives in view:

- (1) To study these relationships in the mesosiderites, because this had not previously been done.
- (2) To study the relationship between the mesosiderites and previously-established trends in the achondrites, with particular reference to howardites.
- (3) To establish whether the eucrites represent a differentiation trend distinct from that defined by the howardites and diogenites, as has been suggested by earlier work (JÉROME and GOLES, 1971).
- (4) To use the observed relationships between the various classes of achondrites and the mesosiderite silicates as a possible means of determining the correct classification of the meteorites Binda and Macibini, on which doubt has been expressed by the writer (this work, and SIMPSON and AHRENS, 1979).

5.2.2 The Ca-Al relationship

The constancy of the Ca/Al ratio in both chondritic and achondritic meteorites has been stated by previous workers in this Department (see Chap. 2). It is indeed remarkably constant in the chondrites (AHRENS et al., 1968) and the howardites (AHRENS and VON MICHAELIS, 1969a). More recently, it became necessary to amend the conclusion of McCARTHY and AHRENS (1971) that the value of this weight ratio is substantially lower in the silicate fraction of mesosiderites (average 0.85) than the average of 1.08 obtained from chondrites and achondrites. SIMPSON and AHRENS (1977) showed, using the new data presented in Table 4.4 of this work, that the average Ca/Al ratio for the silicates of mesosiderites is 1.05, only slightly lower than that of the

howardites. This conclusion was wrongly reported by MITTLEFEHLDT (1979b) and MITTLEFEHLDT et al. (1979).

Table 5.1 lists the Ca/Al ratios for the 42 meteorites on which the present investigation is based. These ratios are very variable in the diogenites, as might be expected from the low concentrations of Ca and Al in these essentially orthopyroxene cumulates. However, considerable variability is present in the eucrites also. Values range from 0.93 in Moama, which is regarded as a cumulate (LOVERING, 1975), to 1.20 in Lakangaon, a eucrite rich in Fe thought to represent a residual liquid in the genesis of eucrites (McCARTHY et al., 1974). This variation is suggestive of a differentiated series of ultramafic to mafic igneous rocks. Plotting of the data on Ca and Al contained in Tables 4.2 and 4.4 (Fig. 5.1) using linear scales shows that the eucrites occupy a slightly elongated field lying across the regression line calculated for the three classes of achondrites represented. Those eucrites regarded as liquids derived from the source area by limited degrees of partial melting (STOLPER, 1977a) lie on or very close to the regression line. The three recognized cumulate eucrites occupy a small field (outlined in Fig. 5.1) on the high-Al, low-Ca side of the line, whereas Nuevo Laredo, Lakangaon, and Stannern fall on the opposite side. This distribution of the eucrites, which is more clearly illustrated in succeeding plots of refractory elements, has been obscured in previous plots of the Ca-Al relationship emanating from this Department by the use of logarithmic scales for the axes (see, for example, Fig. 1 of McCARTHY et al., 1972).

As noted earlier, the relationship between howardites and mesosiderites is of particular interest in this study of inter-element relationships. Fig 5.1 shows that the new analyses of the silicate fractions of mesosiderites fall on a line (not drawn) roughly parallel to, but not coincident with, the achondrite trend. The mesosiderites extend from the

Table 5.1. Ca/Al (wt) ratios in the meteorites included in this investigation

METEORITE	Ca/Al (wt)	METEORITE	Ca/Al (wt)
<u>Table 4.2</u>		Moama	0.931
Malvern (UCT)	1.089	Moore County	1.000
Malvern (BLM)	1.077	Nuevo Laredo	1.193
Binda	1.055	Pasamonte	1.129
Kapoeta	1.073	Serra de Magé	0.967
Molteno	1.086	Sioux County	1.090
<u>Table 4.4</u>		Stannern	1.166
Mincy	1.068	<u>Table 4.8</u>	
Patwar	1.107	Binda	1.081
Estherville	1.016	Bununu	1.030
Mount Padbury	1.049	Chaves	1.113
Vaca Muerta	1.062	Frankfort (F)	1.139
Emery	1.037	Frankfort (T)	1.151
Łowicz	1.017	Malvern	1.104
<u>Table 4.6</u>		Malvern	1.093
Vaca Muerta	1.092	Yamato 7308	1.296
Łowicz	1.035	Zmenj	1.134
<u>Table 4.7</u>		<u>Table 4.9</u>	
Allan Hills 7605	1.064	Ellemeet	1.162
Béréba	1.110	Johnstown	1.603
Cachari	1.078	Shalka	1.643
Haraiya	1.109	Tatahouine	2.012
Juvinas	1.078	Yamato 6902	2.326
Lakangaon	1.201	Barea	0.856
Macibini	1.111	Dyarri Island	1.128

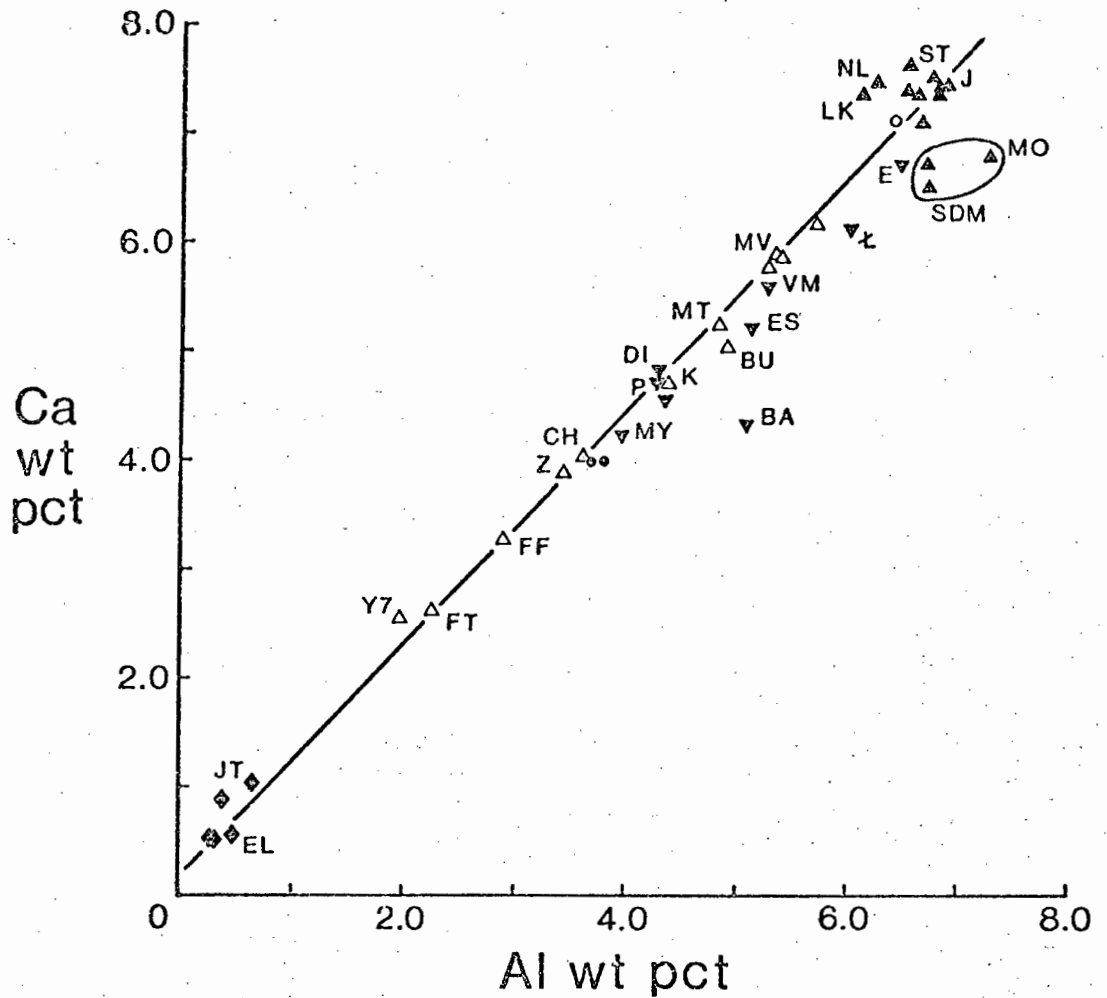


Fig. 5.1. The Ca-Al relationship in the three main classes of achondrites and in the silicate fractions of mesosiderites. The abbreviations used to represent the names of the meteorites are explained in Table 1.3. The symbols used throughout the plots for the various meteorite classes, and the special symbols for Binda and Macibini, are presented in Table 1.4. In this plot, the field occupied by the cumulate eucrites is outlined. Note the position of the analyses of Binda (filled circles) at the low concentration end of the mesosiderite trend, which is roughly parallel to the calculated regression line for the achondrites.

eucrite field part of the way through the howardite range. It is interesting to note that the two analyses of Binda lie at the low concentration end of the mesosiderite trend, far removed from the cumulate eucrites (see the discussion of the classification of Binda in section 5.7). The position of the mesosiderite Barea appears to confirm an earlier suspicion (section 4.7.4) that the value for Ca in its analysis (MASON and JAROSEWICH, 1973) is low. The analysis of Dyarrl Island, the other mesosiderite studied by these authors, does not suffer from this possible fault.

5.2.3 The Ca-Ti relationship

The relationship between Ca and the refractory minor element Ti is shown in Fig. 5.2; values for the Ca/Ti (wt) ratio are listed in Table 5.1a. The differences between the classes of meteorites under investigation are clearly illustrated by the plotting of this element pair. Separate regression lines were calculated for (i) the non-cumulate eucrites, (ii) the howardites and diogenites, and (iii) the mesosiderites. The eucrite line was derived excluding Macibini and Allan Hills 7605. The three cumulate eucrites form a rough extension to the trend. A very good regression line can be drawn through the howardites and diogenites but, unlike that for the Ca-Al relationship, it does not include Macibini. The Ca-Ti plot for the mesosiderites shows a trend distinct from, but sub-parallel to, that of the howardites and, as in Fig. 5.1, extending over the more calcic part of the howardite range. The two analyses of Binda, which are almost identical on this plot, again lie on the mesosiderite trend at its low concentration end, but were not used in the regression calculation. It is of interest to note that both mesosiderite and howardite-diogenite trends pass through the origin of the diagram. The analyses of Dyarrl Island (MASON and JAROSEWICH, 1973) and Bununu (MASON, 1967) were omitted from Fig. 5.2 because of suspect values for Ti (Table 5.1a).

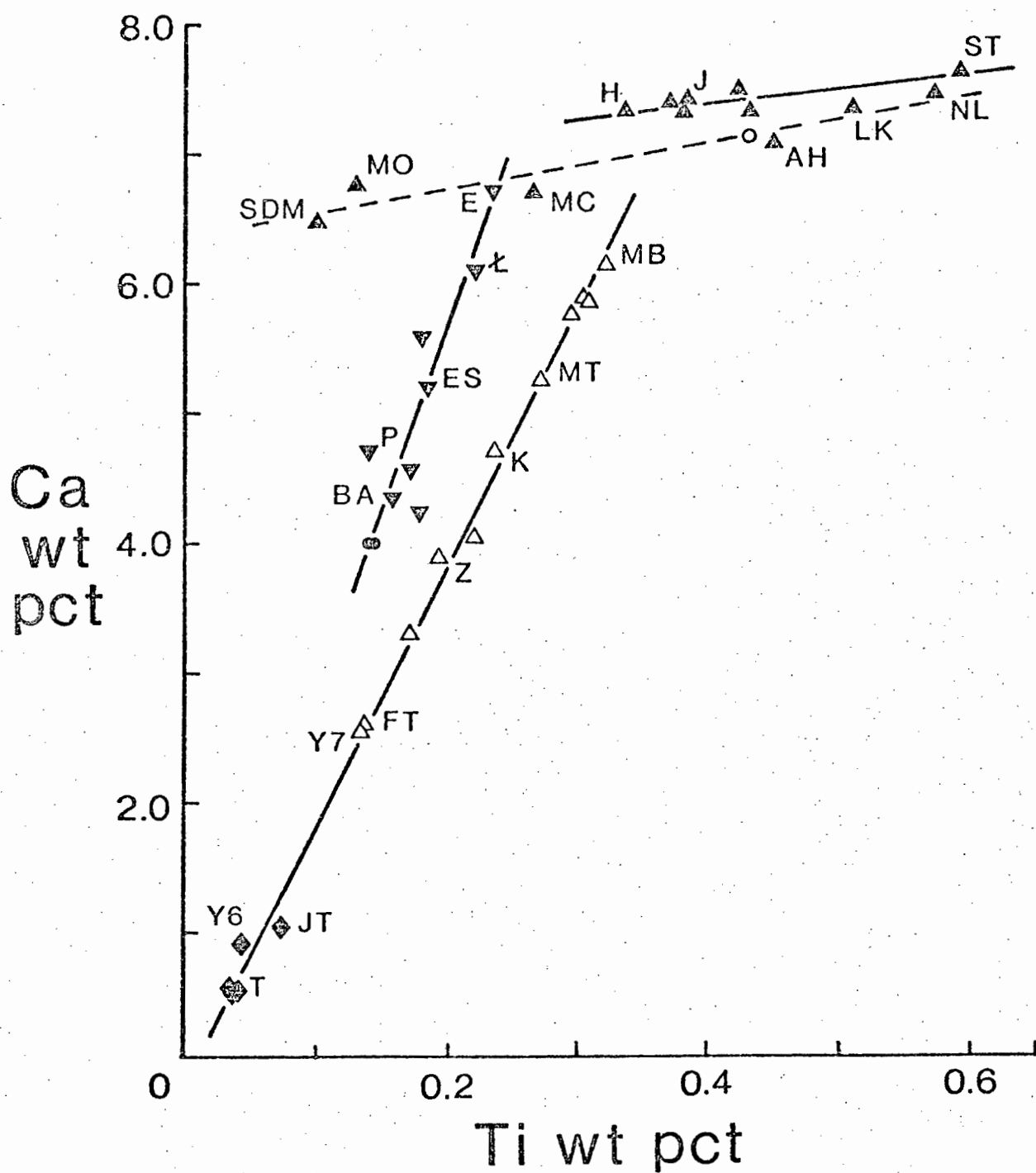


Fig. 5.2. The Ca-Ti relationship in the meteorites studied. Regression lines are shown for the non-cumulate eucrites, the howardites and diogenites, and the mesosiderites. A tentative trend that includes the cumulate eucrites, Allan Hills 7605, Macibini, and the Fe-rich eucrites is indicated by an interrupted line. The Binda analyses plot on the mesosiderite regression line despite not having been used to calculate it.

A further regression can be calculated for the eucrites, and is shown as an interrupted line joining the Fe-rich achondrites Nuevo Laredo and Lakangaon with Allan Hills 7605 and Macibini and, at lower concentrations of Ti, with the three cumulate eucrites. This trend is hypothetical, but must be borne in mind as an alternative but similar path of igneous differentiation if confirmation is found in other inter-element relationships.

5.2.4 The Ca-Ba relationship

All parts of the present investigation that include the study of the behaviour of trace elements suffer from a lack of data, in many instances in meteorites critical to the interpretation. Wherever possible, values have been supplied from the literature, but even when such data can be found, they generally do not compare in reliability with analyses in which major, minor, and trace elements have all been determined on the same sample. Values for the refractory trace elements Ba, Sr, Zr, and Y, and their sources in the literature, appear in Table 4.19.

The Ca-Ba relationship is illustrated in Fig. 5.3, and is similar to that shown for Ca-Ti. Although there are fewer data points, the same three trends are evident. Only howardites could be used to establish the howardite-diogenite trend because Ba was not detected in any of the diogenites studied by McCARTHY et al. (1972). As in the Ca-Ti relationship, Macibini does not lie on this trend nor on that of the non-cumulate eucrites. A regression line can be drawn through Nuevo Laredo, Macibini, Moore County, and Serra de Magé (cf. Fig. 5.2), but there are too few data to justify this. The mesosiderite trend is less definite than in the plot of Ca versus Ti and the distribution of these points is more accurately defined as describing a field (outlined in Fig. 5.3). The analyses of Binda plot close to the calculated regression line for the mesosiderites despite having played no part

in the calculation, and might well be included in the mesosiderite field. They do not coincide with the howardite trend in this plot, and are far removed from the vicinity of the two cumulate eucrites for which Ba data are available.

5.2.5 The Y-Zr relationship

All the inter-element plots involving refractory elements have been drawn without exaggeration of either vertical or horizontal scales in order that the slopes of the enrichment trends present be directly comparable. The Ca-Al plot (Fig. 5.1) showed the mesosiderite trend to be roughly parallel to that of the howardites and diogenites, but some degree of divergence and lateral separation of these trends became apparent in the Ca-Ti and Ca-Ba plots (Figs 5.2 and 5.3), while the eucrites revealed a trend of strong enrichment in Ti and Ba relative to Ca. The angular divergence between the trends is much more marked in plots of refractory trace elements versus Zr, another refractory that is especially useful as an indicator of igneous differentiation. Moreover, the relationship between the eucrite and howardite trends is different for different pairs of elements plotted. In the first of these to be considered, the Y-Zr relationship (Fig. 5.4), the two trends are coincident. Both show a high rate of enrichment in Zr relative to Y. The extreme enrichment of Stannern in both refractories is noteworthy. Unfortunately, the plot suffers from a lack of data on Y, particularly in the cumulate eucrites and in the Fe-rich differentiates, and the element was not detected in the mesosiderites Estherville and Mount Padbury, analyzed in the current investigation. The analyses of Binda plot close to the intersection of the mesosiderite and achondrite trends, but were not included in the calculation of either.

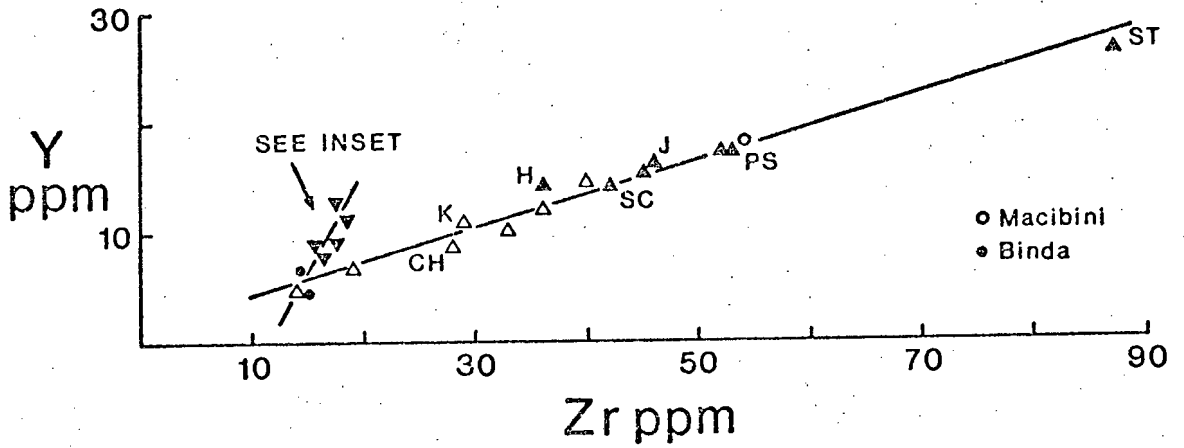


Fig. 5.4. The Y-Zr relationship in achondrites and mesosiderites. A single regression line can be calculated for the achondrites. The position of Binda is ambiguous.

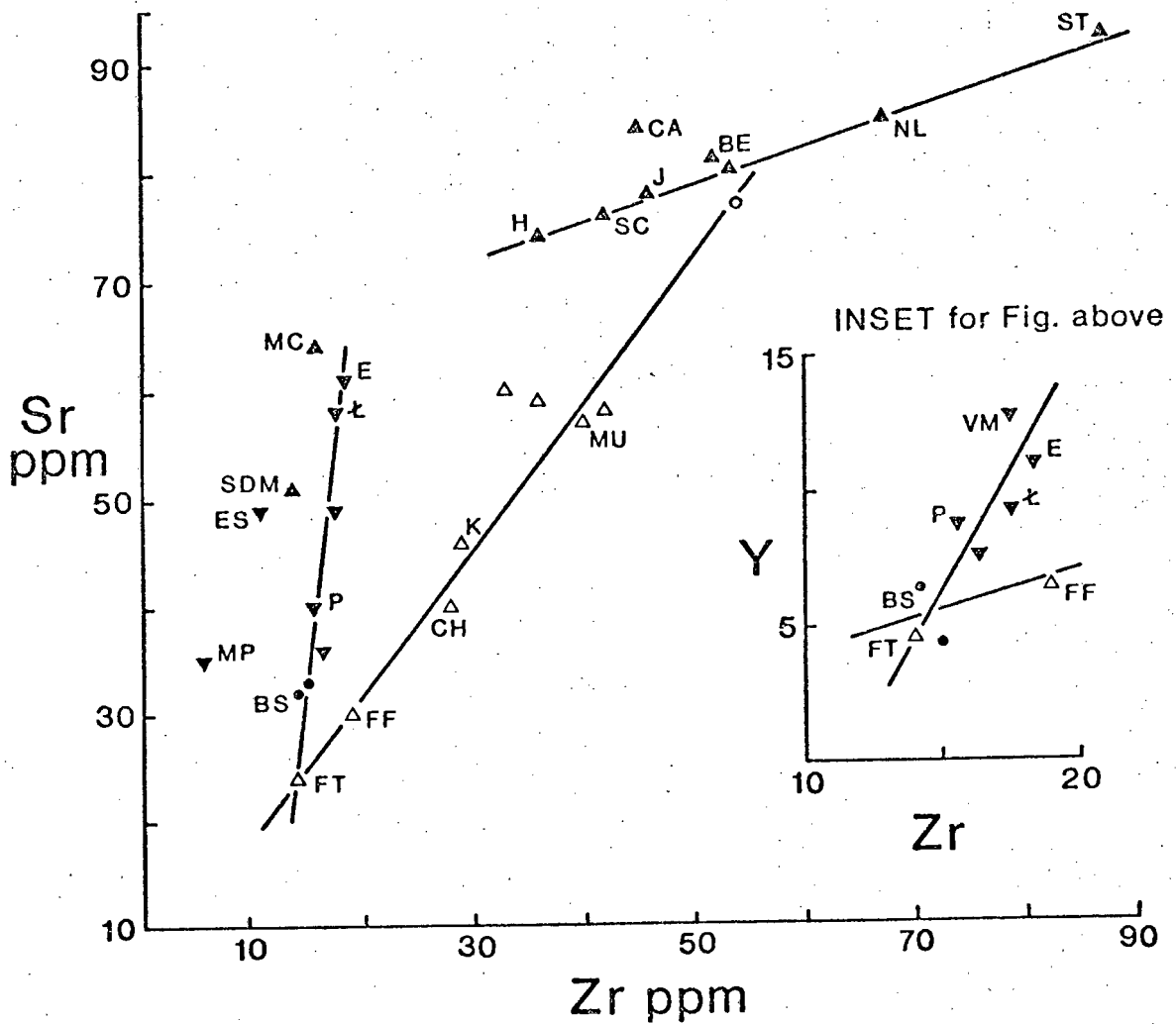


Fig. 5.5. The Sr-Zr relationship in the meteorites studied. Eucrites and howardites can be seen to have different enrichment trends for this element pair, both distinct from that of the mesosiderites, with which Binda is associated.

5.2.6 The Ti-Zr relationship

In this, the second of the series of plots involving Zr, the divergence between the mesosiderite and howardite trends is similar to that in the Y-Zr plot, but the eucrite trend no longer coincides with that of the howardites (Fig. 5.6). The eucrites show a greater rate of enrichment in Zr relative to Ti than do the howardites. The cumulate Moore County lies close to the extension of the eucrite trend, but Serra de Magé, which plots well in other relationships involving Ti, occupies an anomalous position in this figure and in others that include Zr. The reason for this is not apparent, but seems unlikely to be analytical because variation in the value of Zr alone would not rectify the anomaly. The Binda analyses again plot in the vicinity of the intersection of mesosiderite and howardite trends. The position of Nuevo Laredo suggests that Ti may have been over-estimated in its analysis (see also Figs 5.8, 5.12, and 5.20).

5.2.7 The Sr-Zr relationship

The tendency noted in the Ti-Zr plot for the eucrite and howardite trends to diverge is carried still further in this relationship (Fig. 5.5). The regression line for the non-cumulate eucrites is clearly defined. The one aberrant point, that for Cachari, in which Sr may have been over-estimated, was omitted from the calculation. Moore County again lies close to the extension of the eucrite trend, but Serra de Magé plots at a lower level of Sr than any other eucrite (cf. Figs 5.6 and 5.7). Nuevo Laredo shows considerable enrichment in Zr, though not as great as Stannern. The regression line for the howardites in this plot passes through Macibini which, as noted in other figures, does not lie on the eucrite trend. This appears to be the case in relationships where there is wide divergence between the howardite and eucrite trends. The four analyses of Malvern have similar

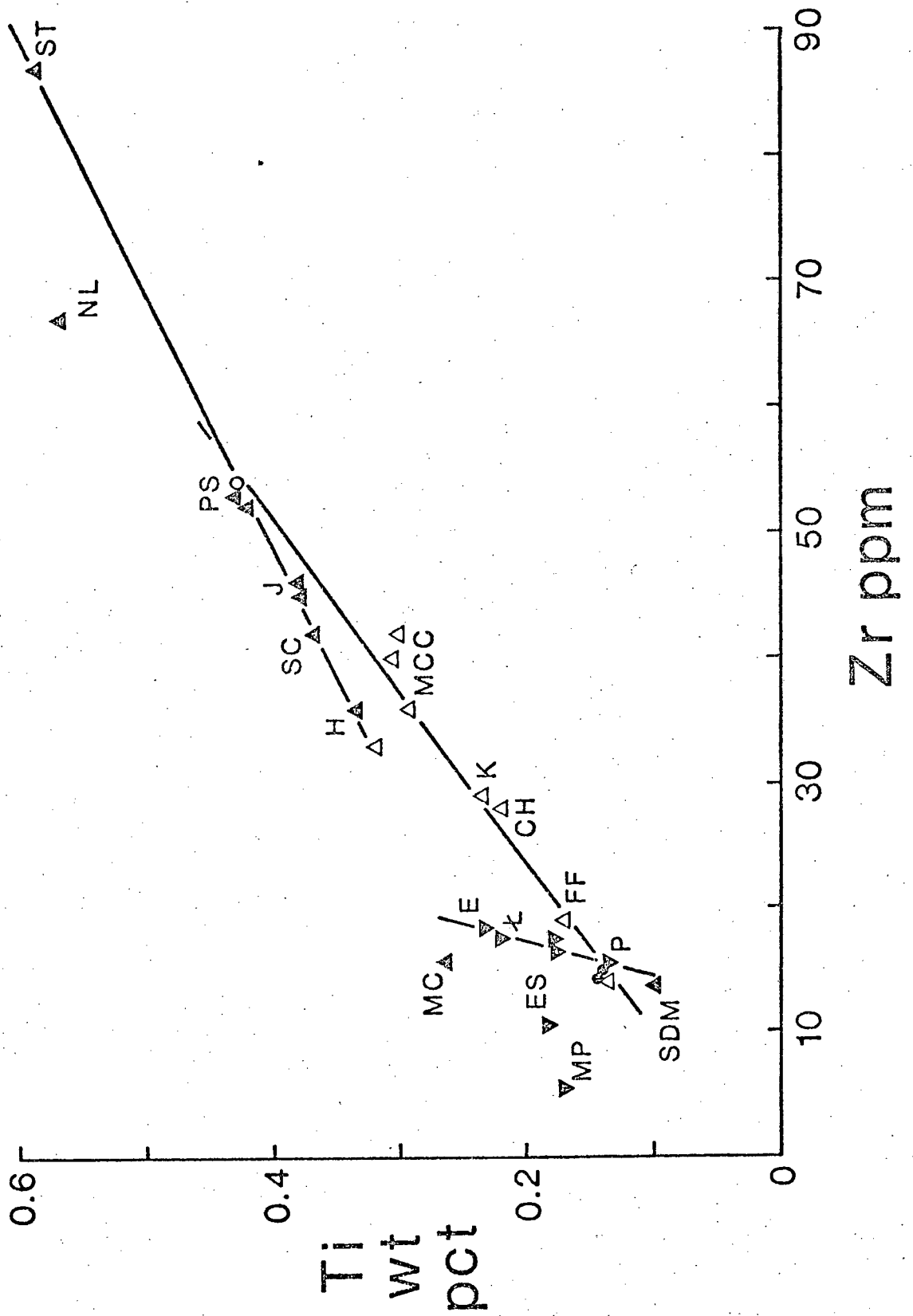


Fig. 5.6. The Ti-Zr relationship shows close similarity to that of Y-Zr (Fig. 5.4), but the eucrite and howardite trends no longer coincide. Binda and Macibini plot ambiguously.

contents of Sr, but show some scatter in their concentrations of Zr. As in previous plots, the mesosiderite trend intersects the howardite trend at a moderate angle and passes through the plotted positions of the two Binda analyses. Estherville and Mount Padbury have low contents of Zr and do not lie on the main mesosiderite trend.

5.2.8 The Ba-Zr relationship

This relationship is very similar to that between Ti and Zr depicted in Fig. 5.6. The non-cumulate eucrites define a trend different from that of the howardites (Fig. 5.7). Cachari and Macibini do not lie on the eucrite trend, but an extension of the regression line calculated for the howardites passes through the point representing Macibini. The mesosiderite trend bears the same relationship to the howardites as in the other plots involving Zr, with Estherville and Mount Padbury plotting off the calculated line, at lower concentrations of Zr. The Binda analyses fall in the general vicinity of the mesosiderites, but are not unambiguously associated either with them or with the howardites. The cumulates Moore County and Serra de Magé are situated, in this instance and in the plots for Ti-Zr and Sr-Zr, in close proximity to the mesosiderite trend, with Moore County roughly aligned with the regression line calculated for the non-cumulate eucrites (Figs 5.5-5.7). The reasons for this situation are not evident, but clarification might result from additional data on Ti, Sr, Zr, and Ba in the cumulate eucrites.

5.2.9 The Ti-Ba relationship

This relationship shows a return to an enrichment scheme similar to that observed for Ca-Al (Fig. 5.1), i.e. all three meteorite classes appear to be uniformly enriched in Ti and Ba, and a single regression line

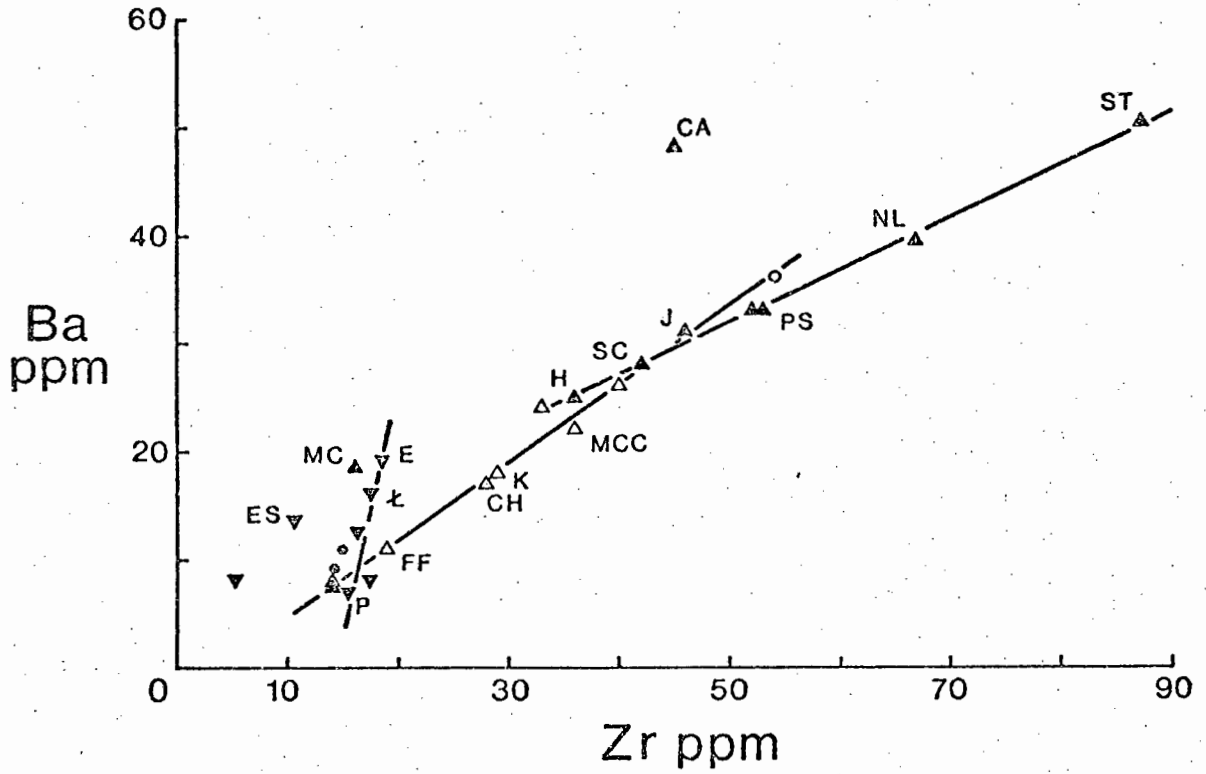


Fig. 5.7. The Ba-Zr relationship shows trends of enrichment similar to those noted for Ti-Zr in the previous figure. The mesosiderite trend is again distinctly different from that of the howardites, and the two cumulate eucrites plotted are associated with it. Binda lies within the mesosiderite field but is close also to the howardite regression line.

could be calculated for all the achondrites investigated, Cachari only being excepted (Fig. 5.8). The mesosiderites, which were not included in the regression calculation, occupy a poorly-defined field at the low concentration end of the trend. The analyses of Binda may be assigned either to this field or to the achondrite trend.

5.2.10 The Sr-Ba relationship

The relationship between these refractory trace elements shows similarities to the relationships of Ca and Ti, Ca and Ba, and particularly Sr and Zr. All three meteorite classes display different slopes of relative enrichment. The mesosiderite analyses do not define a clear trend, but lie in an elongate field with which the analyses of Binda may be associated (Fig. 5.9). The two cumulate eucrites also plot in the proximity of this field and do not lie on an extension of the main eucrite regression line, which is clearly defined. The analysis of Cachari again does not conform to the main eucrite trend, nor does that of Macibini which does, however, plot close to the regression line derived for the howardites.

5.2.11 The Y-Ba relationship

This part of the investigation, again constrained by lack of data, is summarized in Fig. 5.11. A single regression line could be calculated for all the achondrites excluding Cachari, which has an anomalously high concentration of Ba, and Binda, whose classification is one of the objectives of the present study. The mesosiderites form a poorly-defined field lying just above the achondrite trend, and the analyses of Binda plot close to this field and also to the achondrite line.

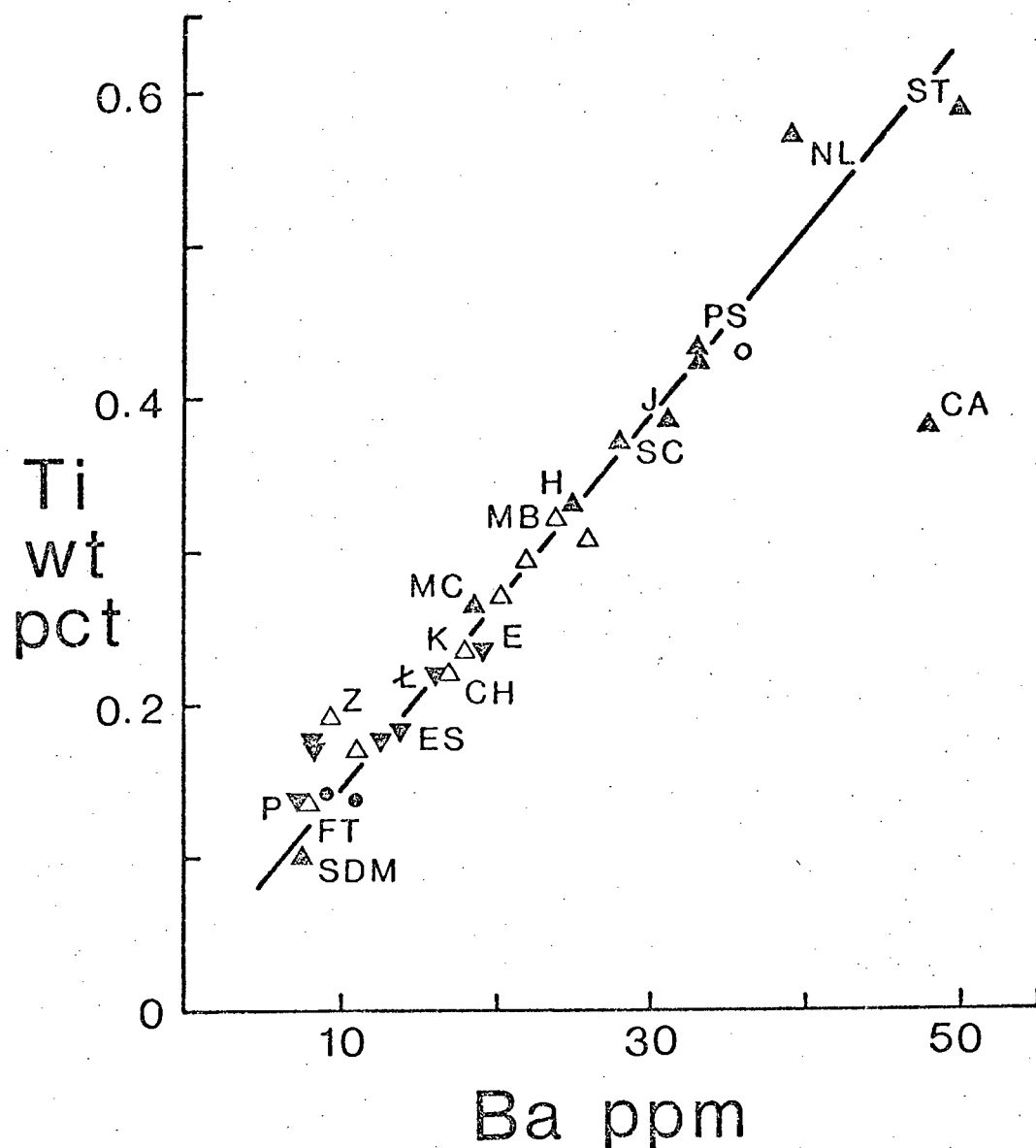


Fig. 5.8. The relative enrichment trends of Ti and Ba in the meteorites studied can be represented by a single regression line calculated for the achondrites. The mesosiderites also conform loosely to the achondrite line. The affinities of the Binda analyses are enigmatic in this relationship.

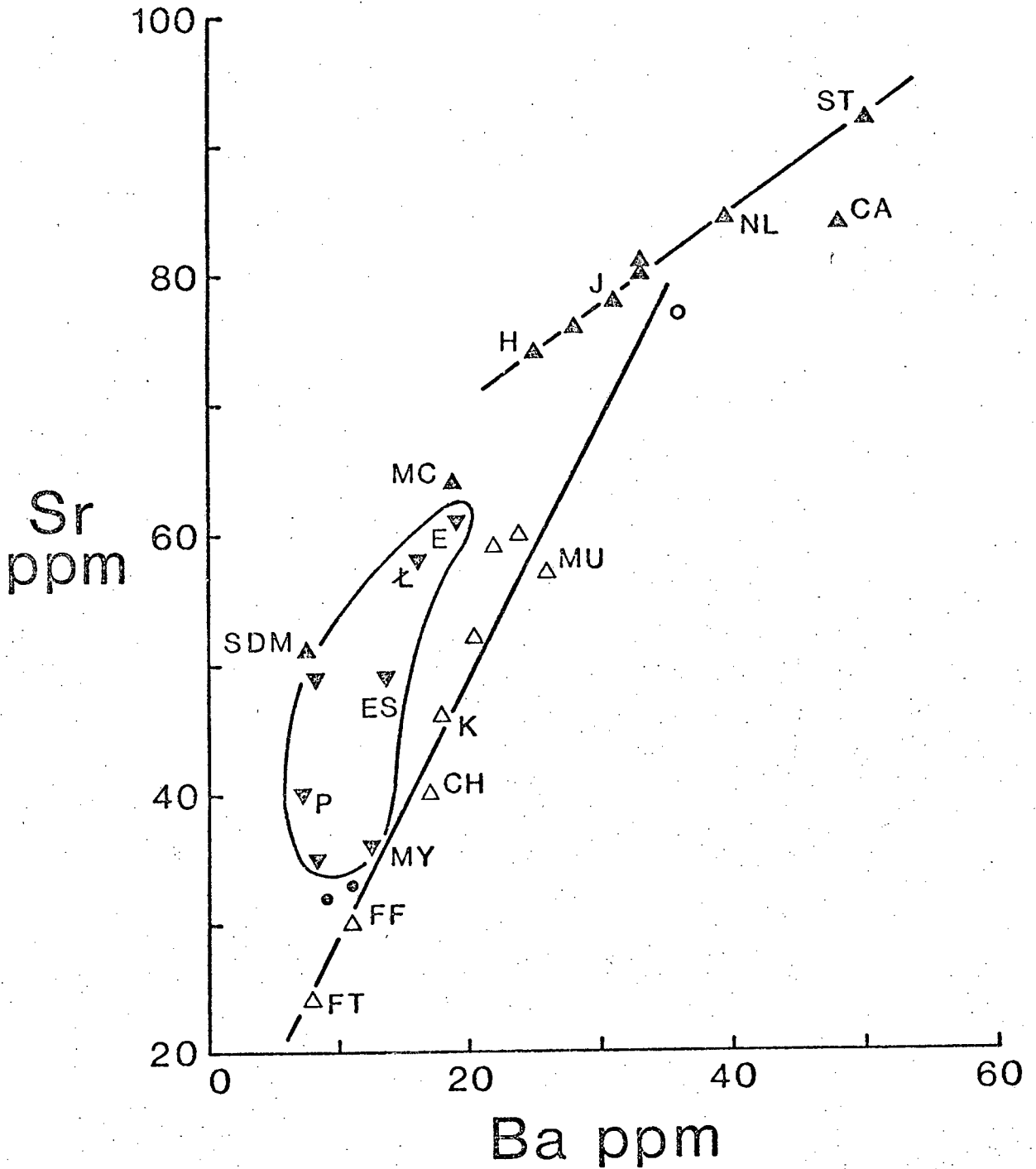


Fig. 5.9. In this relationship, different slopes of relative enrichment are apparent in all three types of meteorite investigated. The mesosiderites do not show a clear trend, but plot in an elongate area outlined in the figure. The analyses of Binda may be associated with this field or with the howardite trend. The cumulate eucrites appear more closely related to the mesosiderite field than to the regression line derived for the non-cumulate eucrites.

5.2.12 The Y-Ti relationship

This relationship is very similar to that described above for Y and Ba, and is depicted in Fig. 5.10. The regression line drawn is based on the achondrite data only (excepting Binda), and the mesosiderite analyses bear the same relation to this trend as that seen in Fig. 5.11.

5.2.13 The Y-Sr relationship

Different slopes of relative enrichment for this refractory element pair are present in eucrites and howardites (Fig. 5.13). Macibini does not plot on the eucrite trend, but may lie on the extension of the howardite trend. The mesosiderites are rather scattered in their distribution. They plot around the howardite line and appear to diverge from it slightly. The affinities of Binda are ambiguous in this relationship.

5.2.14 The Ti-Sr relationship

The trends suggested by the plotting of the Y-Sr relationship are more clearly established in the study of the Ti-Sr pair (Fig. 5.12). The resultant plot is similar to that of Ca-Ti (Fig. 5.2), merely reversed in orientation. Regression lines can be calculated for all three meteorite classes, that for the eucrites diverging considerably from the other two, which are sub-parallel. The cumulate eucrites plot on the main eucrite trend, but Macibini is not unambiguously associated with either the eucrites or the howardites. The points representing Binda do not lie on the howardite trend. Instead, they are situated at the low concentration end of the mesosiderite field, though off the regression line derived for five of the seven mesosiderite analyses. In both this and the previously described plot (Fig. 5.13), Cachari does not conform with the other non-cumulate eucrites. The subsidiary eucritic trend tentatively illustrated in the Ca-Ti plot

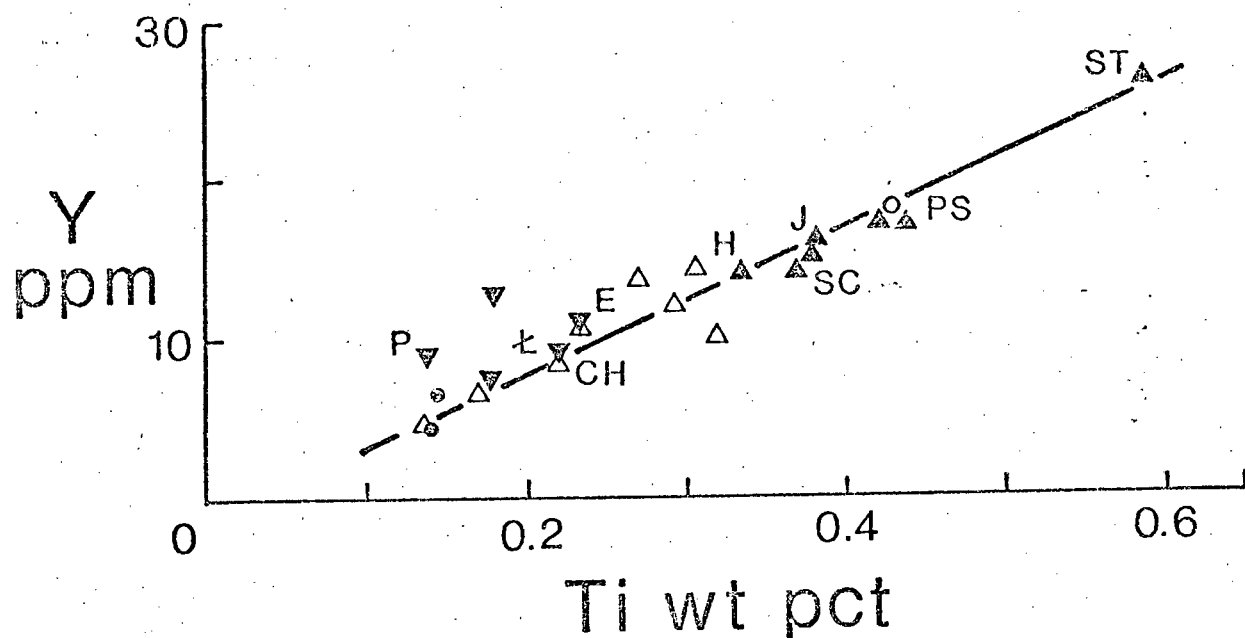


Fig. 5.10. The Y-Ti relationship can be represented by the single regression line shown, which is derived from the achondrites (with the exception of Binda). The mesosiderite field is displaced from this line in the direction of higher concentrations of Y.

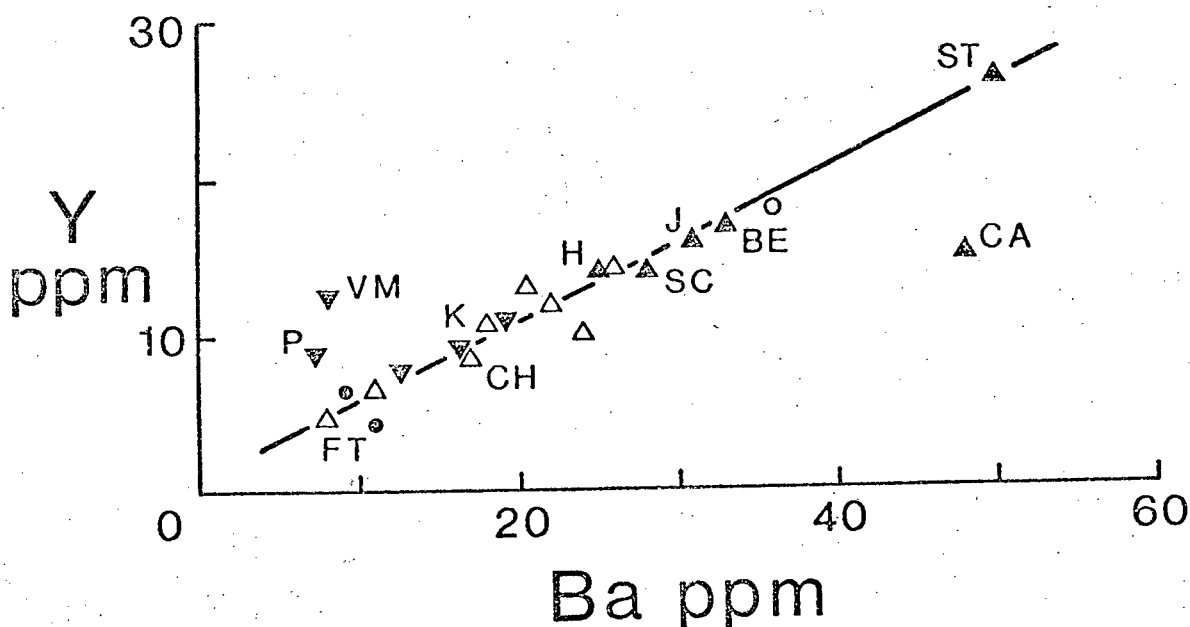


Fig. 5.11. The plot of Y versus Ba is very similar to that for Y and Ti. The mesosiderite field again does not coincide with the achondrite trend, and there is ambiguity in the relationship of Binda to the other meteorites plotted.

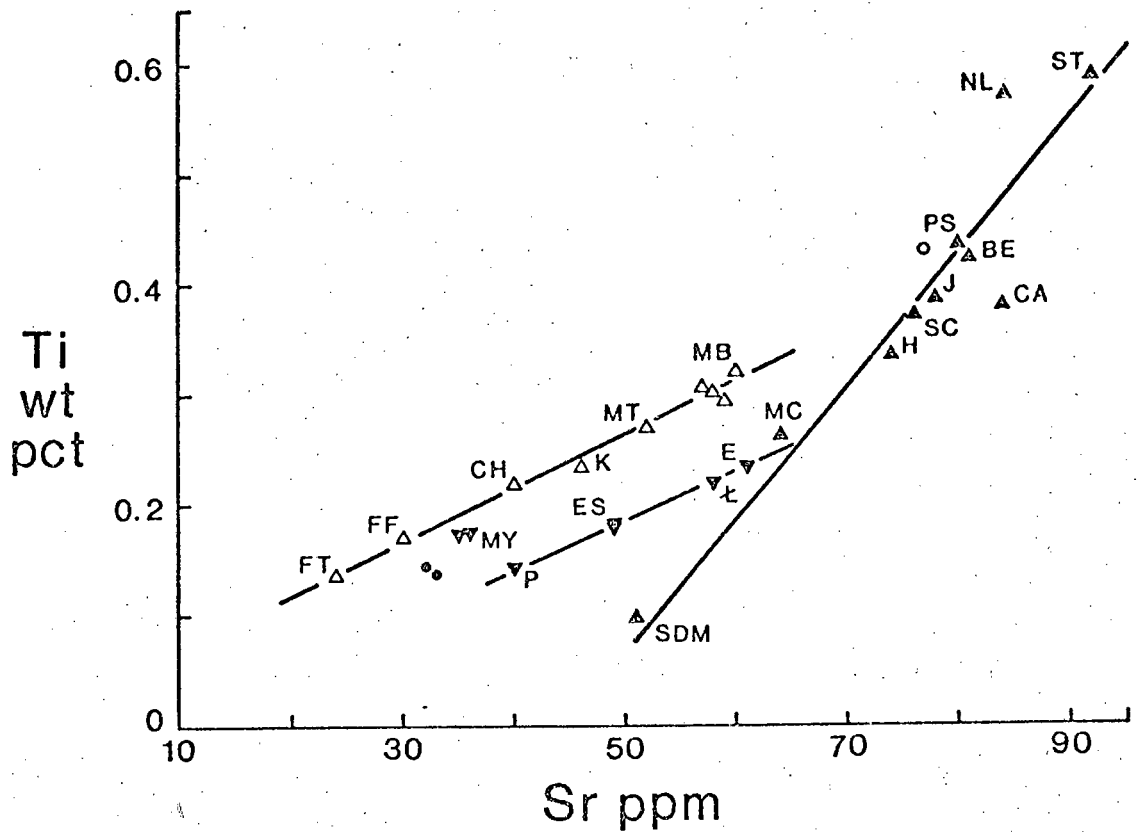


Fig. 5.12. Each of the meteorite classes studied displays its own enrichment trend in this relationship. That for the mesosiderites is roughly parallel to the howardite trend, but displaced from it. Binda does not fall on the howardite trend, but may be associated with the mesosiderite field. Macibini remains enigmatic in this plot.

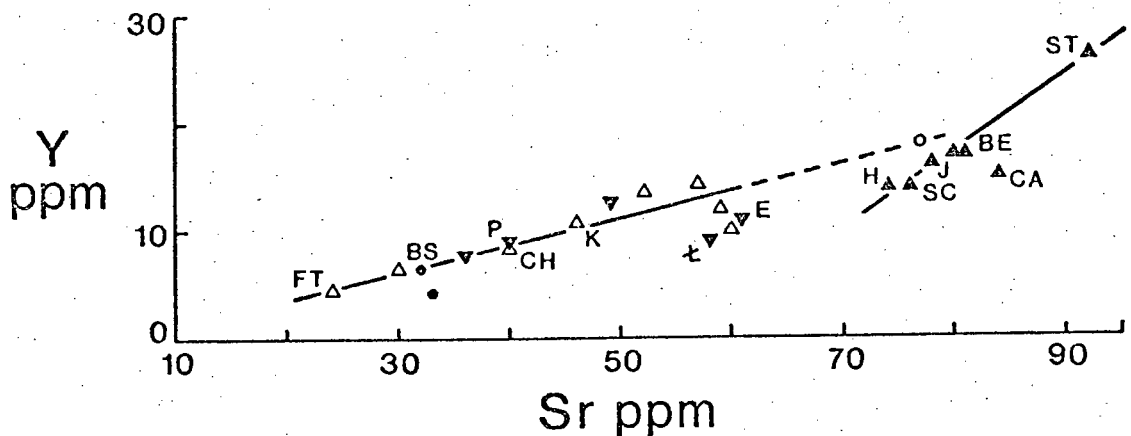


Fig. 5.13. The Y-Sr relationship is similar to that of Ti-Sr, although there are fewer data points and the trends are less well established. Macibini does not plot on the eucrite line, and may lie on an extension of the howardite trend. Binda is ambiguously situated in this figure.

(Fig. 5.2) is possibly present in the Ti-Sr relationship also, embracing in this instance Nuevo Laredo, Macibini, Moore County, and Serra de Magé.

The foregoing examination of relationships between pairs of refractory elements in the analyses of the 42 meteorites investigated has shown that considerable variation is present in the behaviour of these elements in the three meteorite classes considered. The implications of this variation will be discussed in Chap. 9.

5.3 RELATIONS BETWEEN REFRACTORY AND NON-REFRACTORY ELEMENTS

As explained earlier (section 5.2.1), the emphasis in this investigation was placed on the refractory elements. This was partly necessitated by the standard analytical techniques employed in this Department and the consequent impracticability of determining non-refractory elements of potential interest, e.g. Na and K, that occur in low concentrations. Accordingly, this part of the investigation was restricted to one pair of elements - a re-examination of the relationship between Ca, a refractory element, and Mg, a non-refractory, using the data on achondrites and mesosiderites employed throughout the present study.

5.3.1 The Ca-Mg relationship

The inverse relationship between these elements in basaltic achondrites was first described by AHRENS and VON MICHAELIS (1969b), using XRF data, not 'wet' chemical methods as stated by BUNCH (1975, p. 486). It was later re-examined, using only the new data on howardites and the silicate portions of mesosiderites acquired in the present investigation, by SIMPSON and AHRENS (1977). Here the scope is widened to include diogenites, eucrites, and additional howardites. Fig. 5.14 illustrates the relationship

in which the diogenites, the howardites, and those eucrites thought to represent partial melts of their source regions, or slightly fractionated derivatives from these melts, all lie on a clearly defined trend. The highly fractionated eucrites do not plot on this trend but may, with the 'primary' types, define a subsidiary differentiation trend lying at a slight angle to the main achondrite regression line and indicated in the figure by an interrupted line. Macibini plots at the supposed junction of these trends. The two analyses of Binda plot in almost identical positions on the achondrite line. Five of the mesosiderites analyzed in this study define a trend exactly parallel to that of the achondrites but at higher concentrations of Mg and Ca. The two remaining mesosiderites analyzed in this laboratory - Patwar and Vaca Muerta - occupy positions intermediate between these trends, while the published analyses of Barea and Dyarrl Island plot close to the achondrite line. The Ca/Al ratio of Barea is suspiciously low (Table 5.1 and Fig. 5.1), but this is attributed to over-estimation of Al rather than a low value for Ca because the meteorite plots well in the Ca-Ti relationship (Fig. 5.2). Consequently, the plotted positions of both Barea and Dyarrl Island are regarded as valid in the Ca-Mg relationship under consideration. Within the limits of the available data, therefore, it can be speculated that three parallel or sub-parallel trends exist in the mesosiderites in this particular relationship - the 'main' trend, that suggested by Patwar and Vaca Muerta, and a trend coincident with the achondrite line comprising Barea, Dyarrl Island, and probably the two analyses of Binda. The possible significance of these observations will now be considered.

5.3.2 Possible implications of the Ca-Mg relationship

Examination of the major element analyses of the howardites and mesosiderites plotted in Fig. 5.14 (see the tables in Chap. 4) showed that

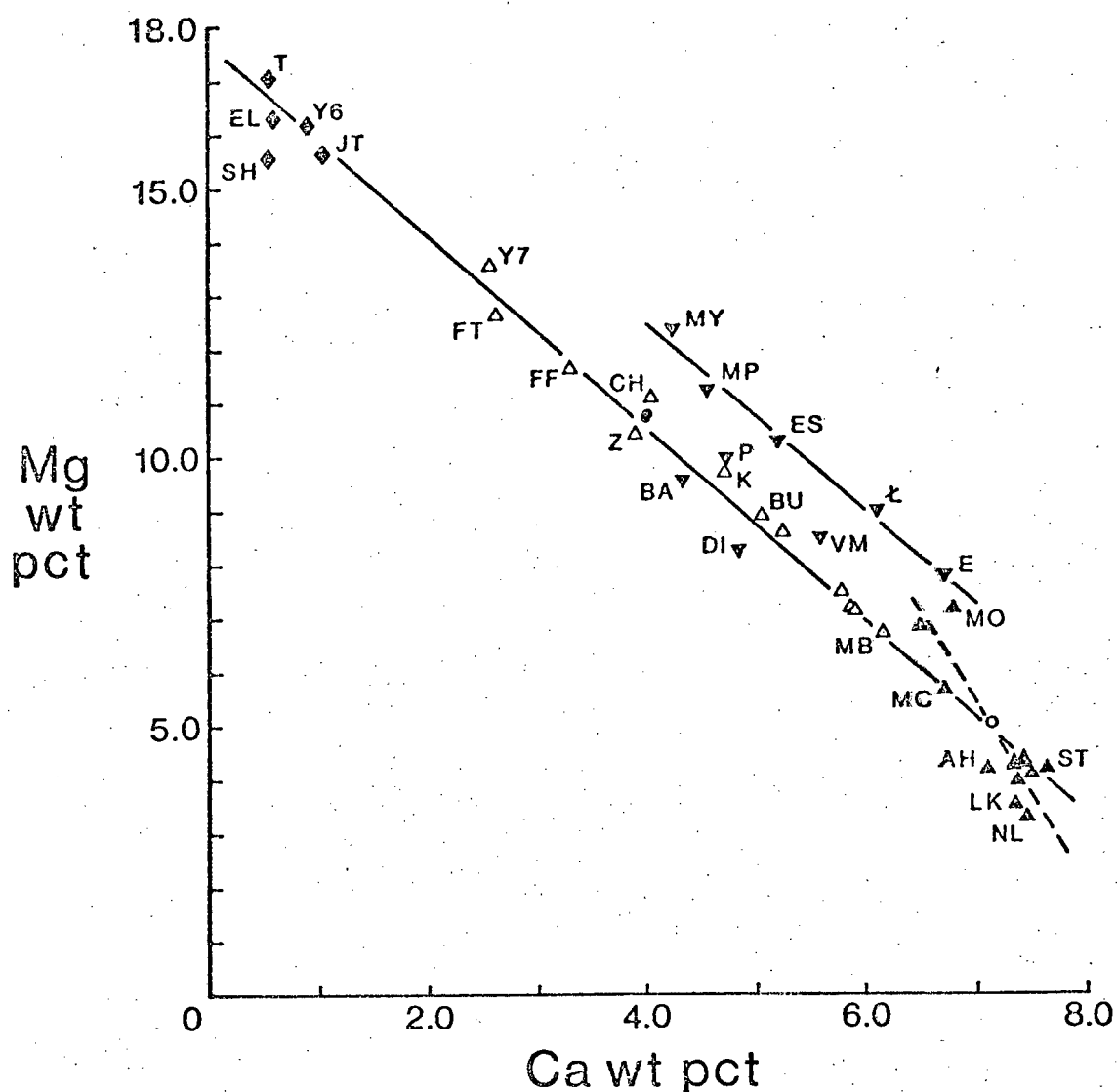


Fig. 5.14. The inverse Ca-Mg relationship previously established on a more limited scale is valid for all the meteorites investigated. A single regression line can be drawn that encompasses all the achondrites, and the 'main' mesosiderite trend lies parallel to it. Barea, Dyarri Island, and the two analyses of Binda appear to be associated with the achondrites, while Patwar and Vaca Muerta occupy intermediate positions. A possible regression for the eucrites is indicated by an interrupted line. Eucrites regarded as primary, or near-primary, melts plot on the achondrite trend close to its junction with the suggested eucrite differentiation trend.

the salient difference between meteorites falling on the various trend lines distinguished in the Ca-Mg plot lies in their contents of FeO. The concentration ranges presented in Table 4.11 disguise the fact that the five mesosiderites that make up the 'main' trend in Fig. 5.14 have contents of FeO little greater than half those of the howardites, while Dyarll Island and Binda contain amounts of the oxide more typical of howardites in particular and achondrites in general; Patwar, Vaca Muerta, and Barea show concentrations intermediate between the two extremes. There is thus a rough correspondence between FeO content in the mesosiderites and their behaviour in the Ca-Mg relationship, and this attracted the attention of the writer. It suggested that various degrees of oxidation of the original content of metallic Fe are represented in the mesosiderites studied, and that those samples with the lowest contents of oxidized Fe - i.e. those that constitute the 'main' mesosiderite trend - are more primitive than the more highly oxidized examples. Furthermore, because some metal-poor mesosiderites have contents of FeO similar to those of the howardites (which are considered by the present investigator and other workers in the field to represent mixtures of a variety of source materials related to one another by differentiation processes), the possibility suggested itself that the material of the crust of the achondrite parent body may have been formed from a mesosiderite-like zone in the body by further oxidation of metallic Fe residual in the silicates of the outermost part of that zone. These outer regions are likely to have had lower contents of metal than more-deeply buried mesosideritic material because of more complete segregation of metal and silicates. Consequently, oxidation of the metal may have been almost complete in the crustal materials (from which the achondrites were derived), but may have diminished with depth to give the varying degrees of oxidation postulated for the mesosiderites.

Table 5.2, compiled from the data of the present investigation supplemented from Appendix IIC of WASSON (1974) and other literature sources, lends some support to this tentative hypothesis. The metal contents of the listed mesosiderites show a rough inverse correlation with the concentrations of FeO determined in their silicate fractions (Tables 4.4 and 4.10). Members of the 'main' trend have averaged contents of about 50% of metallic Fe, whereas the mesosiderite whose silicate fraction most closely approximates a typical howarditic bulk composition - Dyarri Island - has a mere 15.8%. Patwar and Vaca Muerta, which define a possible intermediate trend in Fig. 5.14, contain intermediate amounts of metal. Binda is virtually metal-free (Chap. 3) and cannot therefore be assessed in this way, and Barea is anomalous in terms of the hypothesis both in its content of metal and of FeO. Cognizance must, however, be taken of the fact that both Patwar and Vaca Muerta, though poor in metal, have unusually high contents of FeS (Table A9.2). In Table 5.2, therefore, an attempt is made to assess the total Fe present in eight of the nine mesosiderites investigated; the absence of data on the amount of metal present in Mount Padbury prevented the necessary calculations from being carried out, but the analysis in McCALL (1966) gives total Fe as 51.33%. The summations of the bulk percentages of Fe present in metal, in troilite, and in the silicates of these eight meteorites lie mainly in the narrow range 52% - 57%. Patwar is only a little short of this range, and Dyarri Island is the only real exception with a total of 29%. Some check on the validity of these estimates may be obtained from the close agreement existing between the total calculated for Emery in the present study and the figure of 53.58% given by MASON and JAROSEWICH (1973). Despite the crudity of the approach employed, therefore, the rough equality of the contents of total Fe of seven of the mesosiderites appears to point to their origin from a common source, or similar sources. No explanation for the Fe-deficiency

Table 5.2. Metal contents (wt%) of the mesosiderites included in the present investigation, and estimates of their total contents of Fe based on these values (supplemented, where necessary, from the literature)

Meteorite	Metal(%)	Metallic Fe (%)		Silicate Fe(%)	FeS (%)	Sulphide Fe(%)	Total Fe (%)
	This work	This work	Wasson (1974)				
Mincy	52.2	48.4	--	3.24	0.71	0.45	52.1
Patwar	38.4	34.6	32.0	7.01	11.66	7.41	47.7
Esther-ville	*	--	51.0	4.06	2.88	1.83	56.9
Mount Padbury	*	--	--	--	--	--	--
Vaca Muerta	44.9	41.0	42.8	5.81	9.23	5.86	53.6
Emery	63.0	58.6	45.1	2.26	0.41	0.26	54.4
Łowicz	52.9	48.8	54.5	2.91	0.32	0.20	54.8
Barea	--	--	50.2	4.53	1.62	1.03	55.8
Dyarrl Island	--	--	15.8	11.76	2.32	1.47	29.0

- Notes:
1. Samples marked * were obtained as non-magnetic separates (see Table 1.1).
 2. Averaged values of metallic Fe were used in the summation of total Fe.
 3. 'Silicate' Fe was calculated from the observed metal contents (Col. 1) and the data of Table 4.4. The value for Estherville was derived from the metal content of 56.4% reported by Powell (1971). The calculations for Barea and Dyarrl Island were based on the values of 56.55% and 17.49% respectively (Mason and Jarosewich, 1973) and the data of Table 4.10.
 4. Values for FeS were derived from the observed metal contents and the data of Table A9.2 except for Estherville (Nelen and Mason, 1972), and Barea and Dyarrl Island (Mason and Jarosewich, 1973).

of Dyarri Island suggests itself other than, possibly a different source region.

The inverse relationship between metal and FeO in the silicates of the mesosiderites studied raises the question of the applicability of Prior's Rules (PRIOR, 1920), originally formulated for the chondrites, to this group of stony-iron meteorites, and the genetic implications of these observational qualitative 'rules'. Prior's Rules are concisely stated by MASON (1962a):

- (1) The smaller the amount of nickel-iron (in a chondrite), the higher the Ni/Fe ratio in the nickel-iron.
- (2) The smaller the amount of nickel-iron (in a chondrite), the higher the FeO/MgO ratio in the ferromagnesian silicate minerals.

Table 5.3 shows that four of the members of the 'main' trend in Fig. 5.14 form a sub-group with contents of Ni lower than those of the mesosiderites thought to have undergone greater oxidation. Barea and Dyarri Island, with Ni values of 11.0% and 9.5% respectively (MASON and JAROSEWICH, 1973) are grouped with Patwar and Vaca Muerta as might be expected, but Estherville has a higher Ni content than the other 'main' trend mesosiderites. The correspondence of these data and the metal contents listed in Table 5.2 can at best be said to be rough in terms of Prior's first 'rule', but the division based on the proposed higher and lower oxidation states appears to contradict the view of MASON and JAROSEWICH (1973) that the mesosiderites as a group show uniformity of Ni contents. Nor does the statement of these authors, based on preliminary work by the Wasson research group, that Ga, Ge, and Ir are also uniformly distributed in the metal of mesosiderites, suggesting a single source for the metal, seem valid in the light of later work. WASSON et al. (1974) demonstrated that these trace elements (and Ni) show quite wide variability in the metal phase, and that their distribution can be related to the division of the mesosiderites into three sub-groups,

mainly on the basis of metamorphic grade (POWELL, 1971). This study by the Wasson group suggested also that two different types of metal are present in the least metamorphosed mesosiderites (Powell's sub-group 1), to which Patwar, Vaca Muerta, Estherville, and possibly Mount Padbury, belong. Ga can, of course, be associated also with the mesosiderite silicates, but WILLIS (1978) showed, for the seven mesosiderites analyzed in the present investigation, that the distribution of this element in the whole meteorite correlates with its metamorphic grade, as in the metal fractions. The four examples from sub-group 1 display a range of 4.9-6.4 ppm Ga, whereas the remaining three, which are assigned to sub-group 3, have values in the range 8.2-10.1 ppm. FLORAN (1978) proposed that Estherville should be included in sub-group 3, a suggestion supported by the data for Ge and Ir, but at variance with those for Ni and Ga (Table 5.3).

The foregoing discussion indicates that although there appears to be a degree of correspondence with Prior's first 'rule' in the mesosiderites studied, the position is complicated by metamorphism and the possibility that the metal phase may be of more than one type. What does emerge clearly is the lack of uniformity in Ni, Ga, Ge, and Ir in these meteorites, and - of greater significance to the present investigation - the existence of two sub-divisions in the data on these elements, with Patwar and Vaca Muerta invariably falling in the one group while Mincy, Emery, and Łowicz (members of the 'main' trend) equally invariably are in the other. The positions of Estherville and Mount Padbury are ambivalent, but there is an obvious relationship of the two sub-divisions in the data to the petrographic sub-groups of POWELL (1971). In general, the mesosiderites of sub-group 1 have high Ni and low Ga, Ge, and Ir, whereas the more highly metamorphosed examples that Powell assigned to sub-group 3 have low contents of Ni, but relatively high Ga, Ge, and Ir (Table 5.3). Unfortunately no data are available on the concentrations of the three last-named elements in Barea and Dyarri Island.

Table 5.3. Concentrations of Ni, Ga, Ge, and Ir in the mesosiderites analyzed, and their relations to the petrographic sub-groups of Powell (1971)

Meteorite	Ni	Ga Whole meteorite	Ga Metal phase	Ge	Ir	Powell (1971) sub-group
Mincy	7.2	8.2	13.1	52.4	2.5	3
Patwar	9.9	4.9	9.6	39.3	2.1	1
Estherville	9.0	6.4	9.0	52.3	2.7	1 or 3
Mount Padbury	6.10	5.2	8.9	44.9	2.0	1
Vaca Muerta	8.8	5.8	9.6	42.8	2.2	1
Emery	7.0	9.0	11.5	47.1	2.4	3 ?
Xowicz	7.69	10.1	15.3	54.0	2.5	3

Notes: 1. All values are in ppm.

2. All data are taken from Wasson et al. (1974) except the 'whole meteorite' concentrations of Ga (Willis, 1978).

3. Floran (1978) gives an alternative classification of sub-group 3 for Estherville, and confirms the classification of Emery.

Consideration of the applicability of Prior's second 'rule' to the mesosiderites is less complicated. Reference to Table 5.9, which lists the Fe/Fe+Mg (molar) ratios of all 42 meteorites studied, shows that the three mesosiderites with the least metal (Patwar, Vaca Muerta, and Dyarrl Island) have significantly higher Fe/Fe+Mg ratios - determined by the compositions of the ferromagnesian minerals in their silicate fractions - than those with higher contents of metal. The sole exception is Barea, which has a high metal content (56.55%) and a fairly high Fe/Fe+Mg ratio. However, although it alone does not obey Prior's second 'rule', it does group, in terms of the Fe/Fe+Mg ratio, with the other mesosiderites that are thought to represent higher states of oxidation. There appears to be a fair correspondence

between the Fe/Fe+Mg ratios of the mesosiderites and the Powell sub-group to which they belong; those assigned to sub-group 1 have higher ratios than the members of sub-group 3, except for Mount Padbury, tentatively assigned to sub-group 1 by Powell. This correspondence is strengthened by the classification of Barea and Dyarri Island as members of sub-group 1 by FLORAN (1978).

In summary, therefore, the mesosiderites appear to comply, in a general way, with both of Prior's Rules. Similarly, there is a rough correspondence between the sub-divisions proposed for the mesosiderites on the basis of the degree of oxidation of their content of Fe and the petrographic sub-groups of POWELL (1971). In both cases, however, the situation lacks complete clarity because of the inadequacy of the data, and further work would be required to confirm the tentative conclusions stated above.

WASSON (1974) concedes that Prior's Rules apply qualitatively to the various groups of chondrites, and admirably summarizes the operation of these 'rules' as follows (pp. 53-54): "To a first approximation, the Ni, Fe, Mg, Si, and S abundances are the same within all chondrite groups. Providing metal is present, Ni is highly concentrated in the metal; Mg is highly concentrated in the ferromagnesian silicates; and that portion of the Fe which is not bound to S is distributed between the metal and the ferromagnesian silicates. In reduced chondrites most of the Fe is present as metal, and the Ni content of the metal is correspondingly low. With increasing degree of oxidation, more of the Fe is oxidized; the Fe content of the ferromagnesian silicates increases, and since the amount of metal decreases while the amount of Ni remains constant, the Ni concentration of the metal increases as well." Processes such as these are envisaged as having taken place in the mesosiderites also during the proposed progressive oxidation that generated the sub-divisions of this meteorite group and, ultimately, the source materials from which the main classes of achondrites differentiated.

PRIOR (1920) considered that the two empirical principles he had stated operated in conjunction in the genesis of stony and stony-iron meteorites, and postulated the derivation of all meteorites from a common magma. This idea is no longer tenable because oxygen isotope studies have indicated that chondrites formed in a different part of the solar system from achondrites and mesosiderites (TAYLOR et al., 1965; see Chap. 2). It is interesting to note that Prior suggested progressive oxidation as the mechanism by which the various meteorite groups were produced from the proposed common magma. The hypothesis at present under discussion was formulated independently of Prior's writings, arising from the Ca-Mg relationship as previously described, and is restricted to the generation of achondritic source materials (and possible sub-divisions of the mesosiderites) from 'primitive' mesosideritic material. This hypothesis is, of course, the direct reverse of the currently-held idea that mesosiderites were formed by the mixing of Ni-Fe metal and silicates similar to those of the Ca-rich achondrites (PRIOR, 1918; LOVERING, 1962; and POWELL, 1971), more specifically of the howardites (JAROSEWICH and MASON, 1969). It receives some support from the conclusion of STOLPER (1975b) that "A primitive type of mesosiderite could be suitable source material" (for the low pressure partial melting proposed to have taken place in the eucrite parent body).

A hypothesis for the formation, by progressive oxidation of reduced mesosideritic material, of source compositions that were the precursors of the major classes of achondrites has been stated and discussed in the foregoing section. In the section that follows, some quantitative testing of the idea will be carried out.

5.3.3 Testing of the hypothesis of derivation of achondritic source materials from mesosiderites

The first stage of the testing of the hypothesis was based, appropriately, on the Ca-Mg relationship (Fig. 5.14). Using the bulk chemical data presented in the tables of Chap. 4, average chemical compositions were calculated for six different groupings of meteorites. These were: (1) the five mesosiderites of the 'main' trend of Fig. 5.14; (2) Patwar and Vaca Muerta, which occupy an intermediate position; (3) all the achondrites included in the investigation, with the exception of Binda, whose classification is in question; (4) all the basaltic achondrites studied, except Binda; (5) all the howardites in the study, except Binda; and (6) all the howardites analyzed in this laboratory, except Binda. Binda and the two mesosiderites that lie close to the achondrite trend were therefore excluded from this part of the test. The average compositions of these six groupings are listed in Table 5.4, and these were further refined by recalculation after subtraction of their content of P_2O_5 (Table 5.5). This step can be justified on the hypothesis that the high amounts of P in the silicate fractions of mesosiderites were originally contained in the metal, but were oxidized at temperatures above $750^{\circ}C$ to phosphates, principally whitlockite, which occur mainly at metal-silicate boundaries (FUCHS, 1969). Observations by POWELL (1971), MASON and JAROSEWICH (1973), and MALISSA (1974) confirmed that the P-bearing phases either occur in the metal or originated from it. These phases therefore have no true relevance to the variations in the silicate materials under consideration.

The next (and most important) step in the test procedure was the subtraction from the compositions in Table 5.5 of all FeO in excess of the average value of that oxide contained in the mesosiderites of the 'main' trend. This was, in effect, the removal of 'dilution' by FeO produced by the higher degrees of oxidation postulated by the hypothesis, and the

reduction of categories 2 - 6 to a common basis for comparison with the mesosiderites of the 'main' trend, from which they may have originated. The compositions of these categories were normalized to 100% in preparation for plotting of inter-element relationships that might help to assess the validity of the hypothesis.

Before such plotting could take place, however, selection of the achondrite category (Cols 3-6 in Table 5.6) that most closely approximates the average composition of the 'main' trend mesosiderites had to be made. This was accomplished by a least squares procedure that was applied to the intermediate mesosiderites Patwar and Vaca Muerta also, as a check (Col. 2, Table 5.6). The results of this 'goodness of fit' test are set out in Table 5.7. The least sum of the squares of the differences from the composition of the 'main' trend mesosiderites is, predictably, that of the category comprising Patwar and Vaca Muerta. Among the achondrites, however, the best fit is shown by the group of howardites analyzed in this laboratory (Col. 6, Table 5.7). This is closely followed by the category comprising all howardites included in the investigation (Col. 5), and by that made up of all the achondrites studied (Col. 3). The poorest correspondence was therefore shown by the category restricted to the Ca-rich achondrites. It may be concluded from this that the relationship between achondrites and the silicate fractions of mesosiderites that is being studied involves the entire spectrum of achondritic compositions, not merely part of it. The close correspondence of the howardite groups underlines the probability that they represent averaged samples of the entire range of achondrites, excluding only the uncommon varieties that are not considered in the present investigation.

The composition in Col. 6 of Table 5.6 was therefore selected for use in the plotting of inter-element relationships, the first of these being the Ca-Mg relationship. The Ca and Mg values for all the achondrites plotted

Table 5.4. Average chemical compositions of various categories of meteorites, calculated from the data of this investigation

	1	2	3	4	5	6
SiO ₂	53.21	50.86	50.33	49.68	50.54	50.37
TiO ₂	0.329	0.265	0.443	0.513	0.368	0.409
Al ₂ O ₃	9.79	9.00	8.85	10.40	7.88	8.16
Cr ₂ O ₃	1.055	0.967	0.688	0.533	0.729	0.750
FeO*	9.26	14.11	17.54	17.92	17.22	17.36
MnO	0.566	0.531	0.544	0.547	0.536	0.530
MgO	16.75	15.24	13.97	11.51	15.94	15.39
CaO	7.51	7.22	7.21	8.39	6.43	6.65
Na ₂ O	0.29	0.26	0.34	0.40	0.28	0.29
K ₂ O	0.010	0.007	0.031	0.037	0.031	0.027
P ₂ O ₅	1.230	1.552	0.059	0.070	0.053	0.058
TOTAL	100.000	100.012	100.005	100.000	100.007	99.994

Explanation of column numbering (applicable also to Tables 5.5-5.7):

All data are taken from Tables 4.2, 4.4, and 4.7-4.10.

Column 1 - the five mesosiderites analyzed in this investigation that lie on the 'main' mesosiderite trend in Fig. 5.14.

Column 2 - the remaining two mesosiderites (Patwar and Vaca Muerta).

Column 3 - all achondrites studied, excluding Binda (31 analyses).

Column 4 - all basaltic achondrites, excluding Binda (26 analyses).

Column 5 - all howardites studied, excluding Binda (12 analyses).

Column 6 - all howardites analyzed in this laboratory, excluding Binda (10 analyses).

Table 5.5. Average compositions of Table 5.4, recalculated after subtraction of P_2O_5

	1	2	3	4	5	6
SiO_2	53.87	51.66	50.36	49.71	50.56	50.40
TiO_2	0.333	0.269	0.443	0.513	0.368	0.409
Al_2O_3	9.91	9.14	8.85	10.41	7.88	8.17
Cr_2O_3	1.068	0.982	0.688	0.533	0.729	0.750
FeO^*	9.38	14.33	17.55	17.93	17.23	17.37
MnO	0.573	0.539	0.544	0.547	0.536	0.530
MgO	16.96	15.48	13.98	11.52	15.95	15.40
CaO	7.60	7.33	7.21	8.40	6.43	6.65
Na_2O	0.29	0.26	0.34	0.40	0.28	0.29
K_2O	0.010	0.007	0.031	0.037	0.031	0.027
TOTAL	99.994	99.997	99.996	100.000	99.994	99.996

Column numbering as in Table 5.4

Table 5.6. The data of Table 5.5, recalculated after subtraction of FeO* in excess of that in the 'main' group of mesosiderites (Column 1), i.e. after removal of FeO* 'dilution' in the achondrites and other mesosiderites.

	1	2	3	4	5	6
SiO ₂	53.87	54.35	54.84	54.36	54.87	54.78
TiO ₂	0.333	0.283	0.482	0.561	0.399	0.445
Al ₂ O ₃	9.91	9.62	9.64	11.38	8.55	8.88
Cr ₂ O ₃	1.068	1.033	0.749	0.583	0.791	0.815
FeO*	9.38	(9.38)	(9.38)	(9.38)	(9.38)	(9.38)
MnO	0.573	0.567	0.592	0.598	0.582	0.576
MgO	16.96	16.29	15.22	12.60	17.31	16.74
CaO	7.60	7.71	7.85	9.19	6.98	7.23
Na ₂ O	0.29	0.27	0.37	0.44	0.30	0.32
K ₂ O	0.010	0.007	0.034	0.040	0.034	0.029
TOTAL	99.994	(99.51)	(99.16)	(99.13)	(99.20)	(99.20)

Column numbering as in Table 5.4

Factors used in the recalculations to approximate equivalence with Column 1:

Column 2	1.052111
Column 3	1.089016
Column 4	1.093494
Column 5	1.085258
Column 6	1.086886

Table 5.7. Analysis of the recalculated averages of various categories of meteorites (Table 5.6) to establish which achondrite category most closely approximates the mesosiderites of the 'main' trend in Fig. 5.14 (Column 1, Tables 5.5 and 5.6)

2		3		4		5		6	
Diff.	Diff. ²	Diff.	Diff. ²	Diff.	Diff. ²	Diff.	Diff. ²	Diff.	Diff. ²
SiO ₂	0.48	0.23	0.97	0.49	0.24	1.00	1.00	0.91	0.83
TiO ₂	-0.05	0.00	0.15	0.23	0.05	0.07	0.00	0.11	0.01
Al ₂ O ₃	-0.29	0.08	-0.27	1.47	2.16	-1.36	1.85	-1.03	1.06
Cr ₂ O ₃	-0.04	0.00	-0.32	-0.49	0.24	-0.28	0.08	-0.25	0.06
MnO	-0.01	0.00	0.02	0.03	0.00	0.01	0.00	0.00	0.00
MgO	-0.67	0.45	-1.74	-4.36	19.01	0.35	0.12	-0.22	0.05
CaO	0.11	0.01	0.25	1.59	2.53	-0.62	0.38	-0.37	0.14
Na ₂ O	-0.02	0.00	0.08	0.15	0.02	0.01	0.00	0.03	0.00
K ₂ O	-0.00	0.00	0.02	0.03	0.00	0.02	0.00	0.02	0.00
SUM		0.77			24.25		3.43		2.15

Column numbering as in Table 5.4

in Fig. 5.14 were multiplied by the factor used to recalculate the chosen composition (Col. 6) to equivalence with the average composition of the mesosiderites of the 'main' trend (Col. 1). The values for Barea, Dyarri Island, and Binda also were recalculated by means of this factor because of their proximity to the achondrite line in Fig. 5.14, but the factor derived for Patwar and Vaca Muerta (see Table 5.6) was used in the recalculation of their Ca and Mg contents. The new values obtained were plotted with the original data for the five mesosiderites of the 'main' trend. This re-plotting (Fig. 5.15) shows that removal of the 'dilution' effect of varying amounts of excess FeO results in a uniform relationship for this pair of elements in all the achondrites and mesosiderites studied. The separate trends apparent in Fig. 5.14 have merged in a single trend coincident with that of the mesosiderite 'main' trend. The trend of the eucrite series tentatively distinguished in Fig. 5.14 has not, however, been obliterated by the re-plotting (Fig. 5.15).

The outcome of the first stage of the test of the hypothesis appeared satisfactory, therefore, but it was essential to test the validity of the recalculation procedure on other inter-element relationships. While it was realised that inverse relationships would provide the best illustrations of the effect of plotting the recalculated data, those involving Fe were precluded for the obvious reason that the meteorites under consideration had been recalculated in order to make their Fe contents roughly equivalent for the purposes of the test. Relationships involving Si were unsatisfactory because of the limited compositional range and high variability of that element. The Mg-Al relationship was therefore selected for study.

The plot of the original data on Mg and Al in the 42 meteorites studied (Fig. 5.16) shows features similar to the corresponding plot for Ca and Mg (Fig. 5.14). A single regression line could be calculated for all

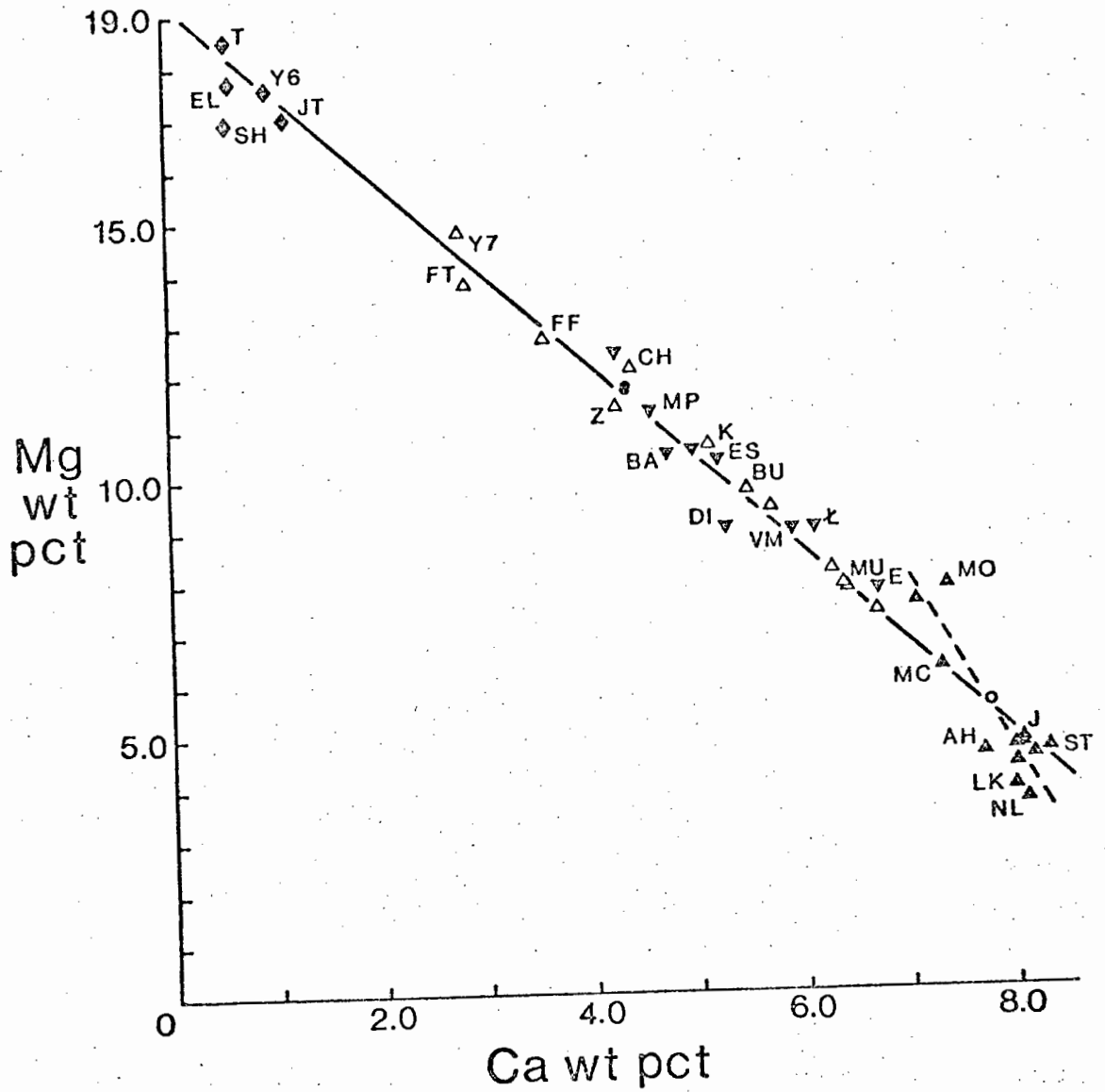


Fig. 5.15. The Mg-Ca relationship, re-plotted using data recalculated as explained in the text. All the meteorites studied now plot on a single regression line, that formerly calculated for the five members of the 'main' mesosiderite trend in Fig. 5.14. This indicates that equivalence can be achieved between achondrites and mesosiderites by removal of the 'dilution' effect of excess FeO produced by the higher degrees of oxidation postulated for the achondrites and some of the mesosiderites.

the achondrites. The Binda analyses were excluded from the calculation, but nevertheless plotted very close to the line, which also passed through, or close to, most of the 'primary' eucrites. A second regression line, exactly parallel to that of the achondrites, could be drawn through the five 'main' trend mesosiderites, and Patwar and Vaca Muerta again occupied positions intermediate between the achondrite and mesosiderite trends. Dyarri Island again plotted close to the achondrite line, but Barea did not because its Al value is too high (see section 5.3.1). A regression line tentatively calculated for the eucrite series intersected the achondrite trend at approximately the position of the 'primary' eucrites. It is interesting to note that, if this eucrite trend is valid, the Mg-Al relationship in the eucrites is a direct, not an inverse, relationship with a slope markedly different from that in the Ca-Mg plot (Fig. 5.14).

Plotting of the Mg-Al relationship with the recalculated data produced essentially the same result as observed for the Ca-Mg pair, although the points show more scatter and the trend is less well defined (Fig. 5.17). It should, however, be borne in mind that the recalculations carried out on the data are necessarily of a somewhat 'rough-and-ready' nature, relying on averages derived from parameters that in themselves are subject to imprecision caused by sampling and analytical error. Nevertheless, within this limitation, the Mg-Al relationship (as re-plotted in Fig. 5.17) appears to support the conclusion indicated by the Ca-Mg relationship, viz. that the achondrites and mesosiderites included in the present study can be brought into correspondence by artificially removing the effects of varying degrees of oxidation of Fe that was originally contained in metal in a reduced mesosideritic source material.

The effect of the recalculated data on the more common type of inter-element relationship, in which the elements are positively correlated,

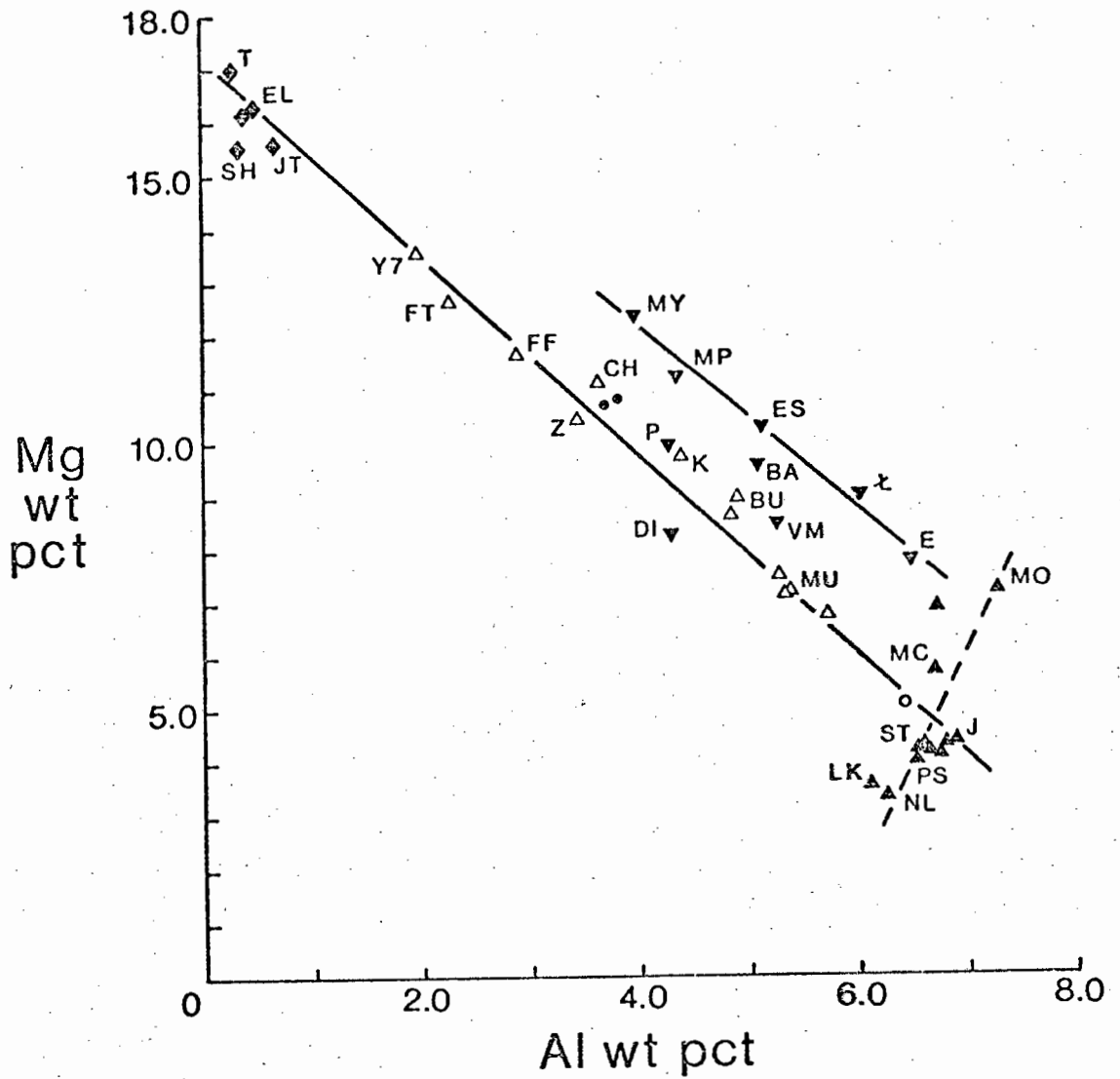


Fig. 5.16. The Mg-Al relationship in the meteorites investigated, using the original data. The diagram shows features similar to the plot of the Ca-Mg relationship (Fig. 5.14); the achondrites define one trend, and five of the mesosiderites another parallel to it, while Patwar and Vaca Muerta occupy positions between them. In this plot, Binda and Dyarrl Island lie near the achondrite line, but Barea is anomalous relative to its position in Fig. 5.14. A regression line tentatively calculated for the eucrite series is shown as an interrupted line with a positive slope, unlike the corresponding trend in the Ca-Mg plot. Most of the eucrites lie close to the intersection of this trend and the main achondrite regression line.

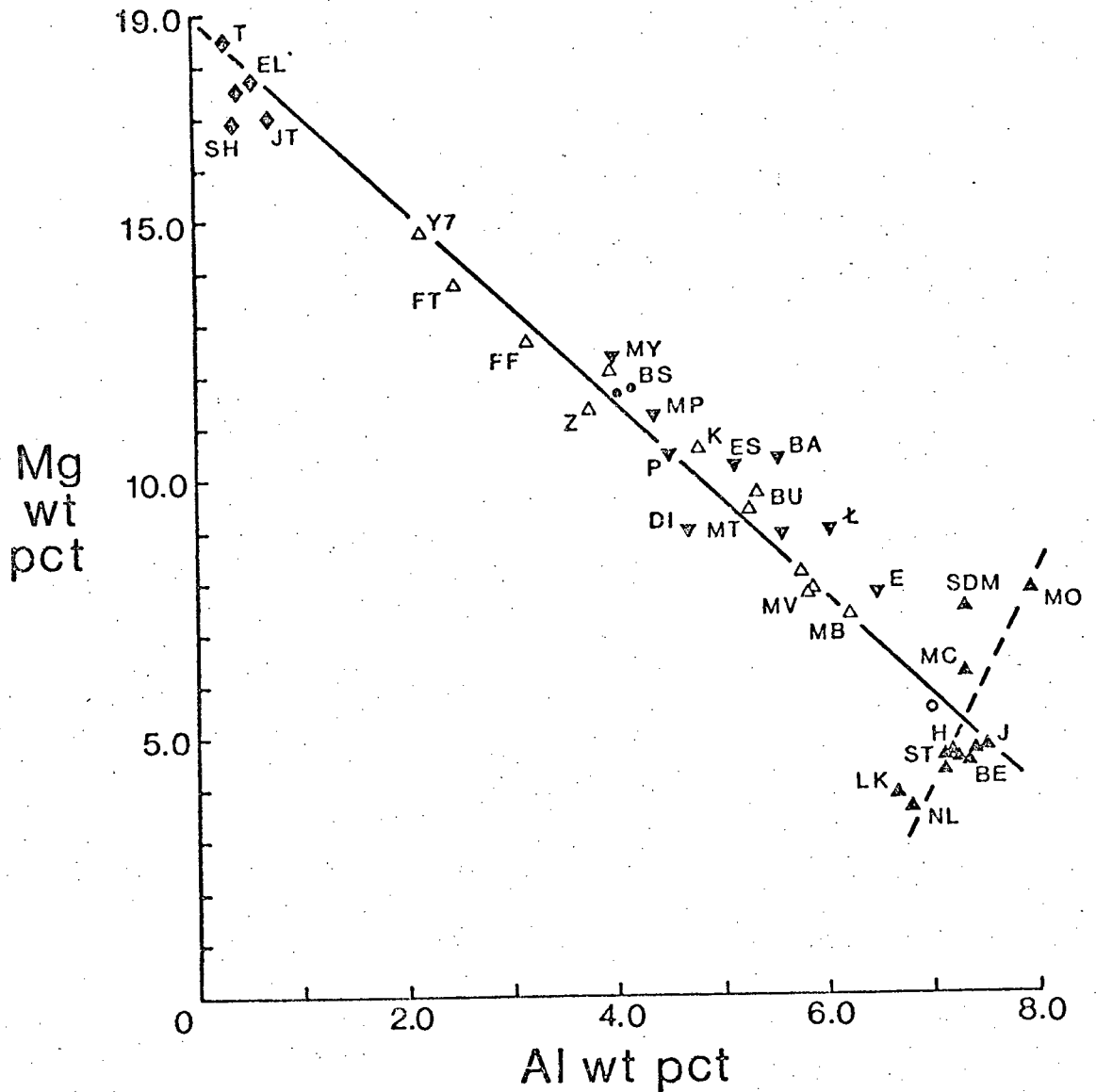


Fig. 5.17. The Mg-Al relationship, re-plotted using recalculated data on the achondrites and some of the mesosiderites (see text). A single regression line can be drawn for all the meteorites plotted, as in the Ca-Mg relationship based on the recalculated data (Fig. 5.15). Although the points in this plot show more scatter than in the previous figure, the re-plotted relationship again suggests that achondrites and mesosiderites can be brought into correspondence by making allowance for oxidation of Fe originally contained in metal in the more reduced types of mesosiderites.

was studied by re-plotting the Ca-Al relationship (Fig. 5.18) and comparing the result with the original plot (Fig. 5.1). As expected, the difference was less apparent than in the inverse Ca-Mg and Mg-Al plots. The concentrations of Ca and Al having been increased by the appropriate factors in all the meteorites except the five 'main' trend mesosiderites resulted in a slight movement of the points representing these meteorites relative to the unmodified mesosiderites. This made possible the calculation of a single regression line for all the meteorites plotted in Fig. 5.18, whereas the regression line drawn in the original plot applied only to the achondrites, while the mesosiderites defined a sub-parallel trend (not depicted in Fig. 5.1) on the low-Ca, high-Al side of the achondrite line. Use of the recalculated data therefore had the effect of diminishing the scatter of the plotted points, and this is interpreted as confirmation of the results more clearly evident from the inverse relationships plotted earlier.

The three inter-element relationships discussed appear to support the hypothesis proposed, but this cannot be said of all the relationships studied in this chapter. Obviously, the recalculation procedure will not produce coincidence where, in direct relationships, the achondrite and mesosiderite trends are divergent and widely separated. This was proved using the Ca-Ti plot (Fig. 5.2). Such conditions are general in the relationships involving trace elements discussed earlier in this chapter. Furthermore, in relationships in which the eucrite trend covers a wide compositional range and lies at high angles to the trends defined by the other achondrites and by the mesosiderites, use of the recalculated data will not effect coincidence of all three trends. In some instances, e.g. Ca-Ti, Ca-Ba, Ba-Zr, and Ti-Sr, the situation is simplified by the fact that the 'primary' eucrites, from which the other eucrites are presumed to have differentiated, lie on the main achondrite trend or on a possible extension of it, thereby effectively

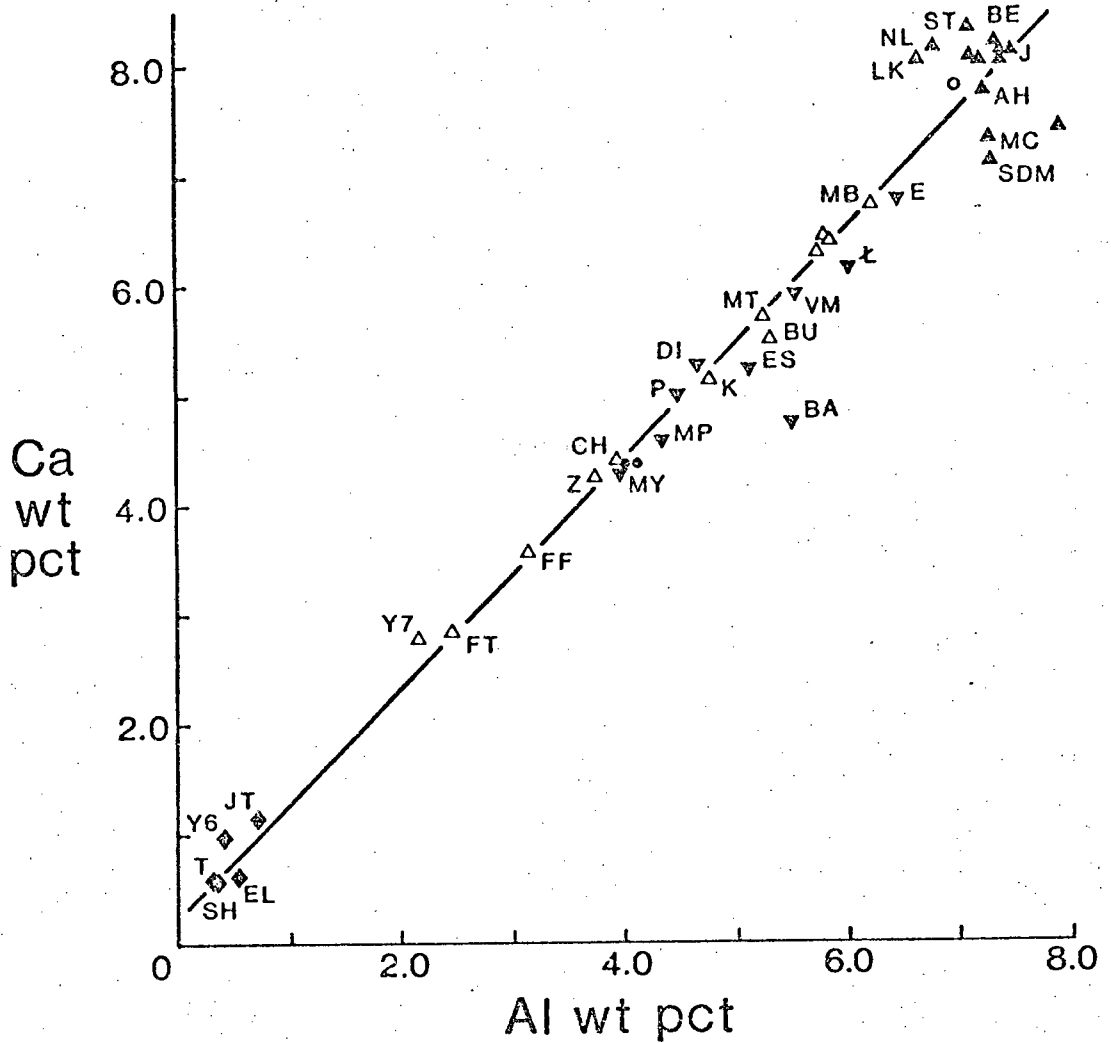


Fig. 5.18. Re-plotting of an element pair with a direct relationship is illustrated by Ca and Al. Comparison with Fig. 5.1 shows that use of the recalculated data for these elements moves the points representing the achondrites and those mesosiderites that may have been more highly oxidized closer to the five mesosiderites of the 'main' trend in Fig. 5.14. The scatter of the points is thereby reduced, enabling the calculation of a single regression line for all the meteorites plotted. This indicates agreement with the results obtained by the re-plotting of inversely related element pairs (Figs 5.15 and 5.17).

reducing the divergent trends to two. However, there are relationships, e.g. Sr-Zr, Ti-Zr, and Sr-Ba, in which this is definitely not so according to the regression lines calculated for the plots of these element pairs. It must be concluded, therefore, that although the testing of the hypothesis indicates its possible validity in terms of the major elements Ca, Mg, and Al, its applicability to minor elements, e.g. Ti, and trace elements cannot be demonstrated.

From the foregoing discussion, it may be presumed that there is closer correspondence between achondrites and the silicate fractions of mesosiderites in the behaviour of the major elements than in that of the minor and trace elements. The reasons for this difference are not understood. Inter-element plots of trace elements in this chapter generally suggest three distinct differentiation series - the eucrites, the mesosiderites, and a third comprising the diogenites and the materials from which the howardites were formed. As noted above, the two achondrite trends may be reconciled in some instances because they intersect at the position of the 'primary' eucrites, while in other plots they merge into one. Thus, in general, the achondrites can be considered as a single series, ranging from the 'primary' eucrites to the diogenites, in terms of both major and trace element behaviour. The mesosiderites, however, exhibit no such consistency. The trend of the series does not consistently intersect the diogenite-howardite trend, nor bear any constant relation to it, as the inter-element plots in this chapter show. There appears to be no known meteorite, or group of meteorites, common to both achondrite and mesosiderite trends in the way that the 'primary' eucrite group links the eucrite series with the howardites and diogenites. Binda, or the howardite Frankfort (T), may be the nearest approach to common ground between the mesosiderites and the achondrites, but this is not a consistent feature of the trace element inter-relationships.

One agency that might be invoked to account for the apparent differences in trace element behaviour between achondrites and mesosiderites is metamorphism, which may have caused some redistribution of trace elements. Most achondrites have undergone little metamorphism, whereas mesosiderites exhibit metamorphic effects ranging from low grade in the members of Powell's sub-group 1 to complete recrystallization in sub-group 3. However, this is not considered to be a satisfactory solution, because the more regular and well-defined trace element trends are defined by mesosiderites of both low and high metamorphic grade. The regularity of these trends suggests that the record of an igneous evolution different from that of the achondrites has survived metamorphism.

The problem therefore remains. Recalculation of the data on some of the major elements supports the suggestion that the source materials of the main classes of achondrites may have been derived from reduced mesosideritic material by progressive oxidation of the metal, whereas the trace element data suggest that the achondrites and mesosiderites followed evolutionary paths separate and distinct from one another.

5.4 RELATIONS BETWEEN NON-REFRACTORY ELEMENTS

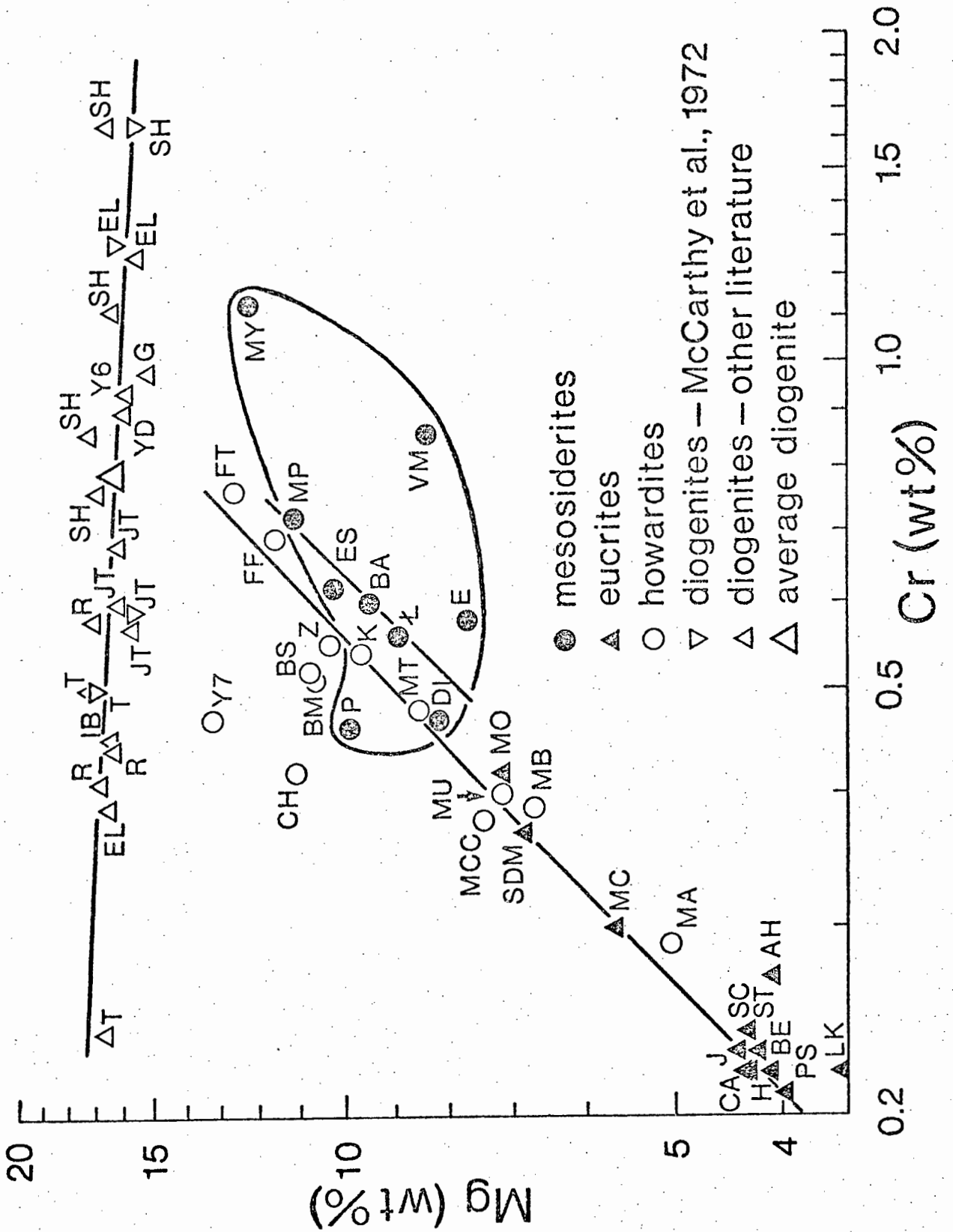
The relationship between one pair only of non-refractory elements - Mg and Cr - was included in the present project. This part of the investigation was published in SIMPSON and AHRENS (1979) and was the work of the senior author. It is merely summarized here in the interest of completing the account of inter-element relationships. The wider topic of the Mg-Cr relationship in terrestrial, meteoritic, and lunar basalts is treated in AHRENS (1976).

5.4.1 The Mg-Cr relationship

Because of the importance of Mg and Cr in diogenites, additional data were taken from the literature to supplement the analyses used throughout this investigation. These data, and their sources, are presented in Table 3 of SIMPSON and AHRENS (1979). The relationship is plotted here in Fig. 5.19, which shows a well-defined positive correlation between Mg and Cr in eucrites and howardites, with the eucrite differentiation series coincident with the trend apparent in the howardites. The supplementary diogenite analyses taken from the literature were not averaged prior to plotting with those used throughout this study and, as expected, show considerable variability that probably arises mainly from the difficulty of sampling relatively coarse-grained cumulates. However, the trend defined by these analyses is clear, and is virtually identical to the regression line calculated for the averaged diogenite data or for the four analyses carried out in this laboratory (McCARTHY *et al.*, 1972). In the diogenites, the almost constant content of Mg is in sharp contrast to the extreme variability shown by Cr. GOOLEY (1972) suggested that this variability might be explained by the origin of diogenites in a layered igneous complex that, like terrestrial analogues, showed rapid vertical variation of Cr in its deepest levels. Deep excavation of the complex by impacting meteorites, or the total disruption of the parent body, would have sampled material with the compositional characteristics of the diogenites. It should be noted that the position of the 'average diogenite' (Fig. 5.19), though sensitive to the wide range of Cr values present, falls close to the basaltic achondrite trend.

The mesosiderites plot in an irregular field (outlined in Fig. 5.19) that lies mainly on the high-Cr side of the achondrite trend. A regression line has been drawn through six of the mesosiderites,

Fig. 5.19. The Mg-Cr relationship in the meteorites studied and in additional diogenites from the literature. The basaltic achondrites show a clearly defined positive correlation that contrasts with the irregular distribution of the mesosiderites. The mesosiderite field is outlined. The regression line calculated for six of the points in this field lies parallel to the eucrite-howardite trend, but may have no real significance. The points representing Binda do not lie on the basaltic achondrite trend, but are close to the mesosiderite field. The diogenites exhibit extreme variability in Cr as opposed to almost constant Mg. The average diogenite composition plots close to the extension of the eucrite-howardite line. Additional abbreviations: G - Garland; I - Ibbenbüren; R - Roda; and YD - diogenite inclusion in Yamato 7308. Sources of supplementary data: FREDRIKSSON et al., 1976; MASON and JAROSEWICH, 1971; UREY and CRAIG, 1953; and YAGI et al., 1978.



approximately parallel to that of the achondrites, but it may have no real significance. The mesosiderites lack the coherence of the achondrites in this relationship, and this may suggest differences in their mode of formation. It is worth noting that the two Binda analyses do not plot on the basaltic achondrite trend, but lie close to the mesosiderite field. As in other relationships examined in this chapter, this may have genetic implications.

5.5 RELATIONS INVOLVING THE Ca/Al RATIO

The Ca/Al ratio has been discussed by earlier investigators in this Department (AHRENS and VON MICHAELIS, 1969a; AHRENS, 1970c), who regarded it as unfractionated, or only slightly fractionated, in the refractory enrichment sequence comprising the various classes of chondrites and the basaltic achondrites. A paper resulting from the present investigation (SIMPSON and AHRENS, 1977) showed that the ratio is not significantly lower in the mesosiderites, as previously contended (McCARTHY and AHRENS, 1971), and Fig. 5.1 in this work confirms this conclusion; achondrites and mesosiderites plot with almost identical slopes.

STOLPER (1977a) re-examined the Ca/Al ratios of eucrites that he had shown to represent liquids produced by small degrees of partial melting of the proposed source material of the achondrites, or by low pressure fractionation of pigeonite and plagioclase from these liquids. He noted that the variations in the ratio in these meteorites are not negligible, and showed that the Ca/Al ratio correlates positively with the concentrations of Ti, regarded as an incompatible element and a differentiation index, present in them and in experimentally produced eucritic liquids (STOLPER, 1977a, Fig. 11). The current investigation extended this study to include the cumulate eucrites, the howardites and diogenites, and the mesosiderites, and

to examine the behaviour of the Ca/Al ratio in relation to other indicators of differentiation.

5.5.1 The relationship between the Ca/Al ratio and Ti

Fig. 5.20 illustrates this relationship in the 42 meteorites studied. However, because of the sensitivity of the parameters plotted, it is necessary first to review what is known of the quality of the data from inter-element relationships plotted earlier in this chapter. Firstly, both parameters are likely to be unreliable in the diogenites on account of the low concentrations of Ca, Al, and Ti present and the consequently high relative errors involved in their determination. More specific comments can be made on certain of the analyses of howardites and eucrites, as follows: the Ca/Al ratio in Allan Hills 7605 appears too low because of under-estimation of Ca, and the Ti content is too high; in Bununu, the ratio is too low because the Al determination is too high, and Ti has been under-estimated; the analysis of Nuevo Laredo appears to contain slightly too much Ti, while that of Serra de Magé has too little; and the Ca/Al ratio of Yamato 7308 may be too high (although it plots reasonably well in Fig. 5.1) as a result of over-estimation of Ca (cf. Figs 5.1, 5.15, and 5.16). In the mesosiderites, the Ca/Al ratio of Barea is far too low, and the Ti content of Dyarri Island is far too high. All of these observations may be verified from previous figures and Table 5.1, and must be borne in mind when the Ca/Al versus Ti plot and subsequent relationships are studied.

In Fig. 5.20, the positive correlation noted by STOLPER (1977a, Fig. 11) in part of the eucrite series is denoted by a solid line. The regression line calculated in the present work for all eucrites included in the study is shown as an interrupted line that does not differ significantly from that drawn from Stolper's diagram. The cumulate eucrites fit well on

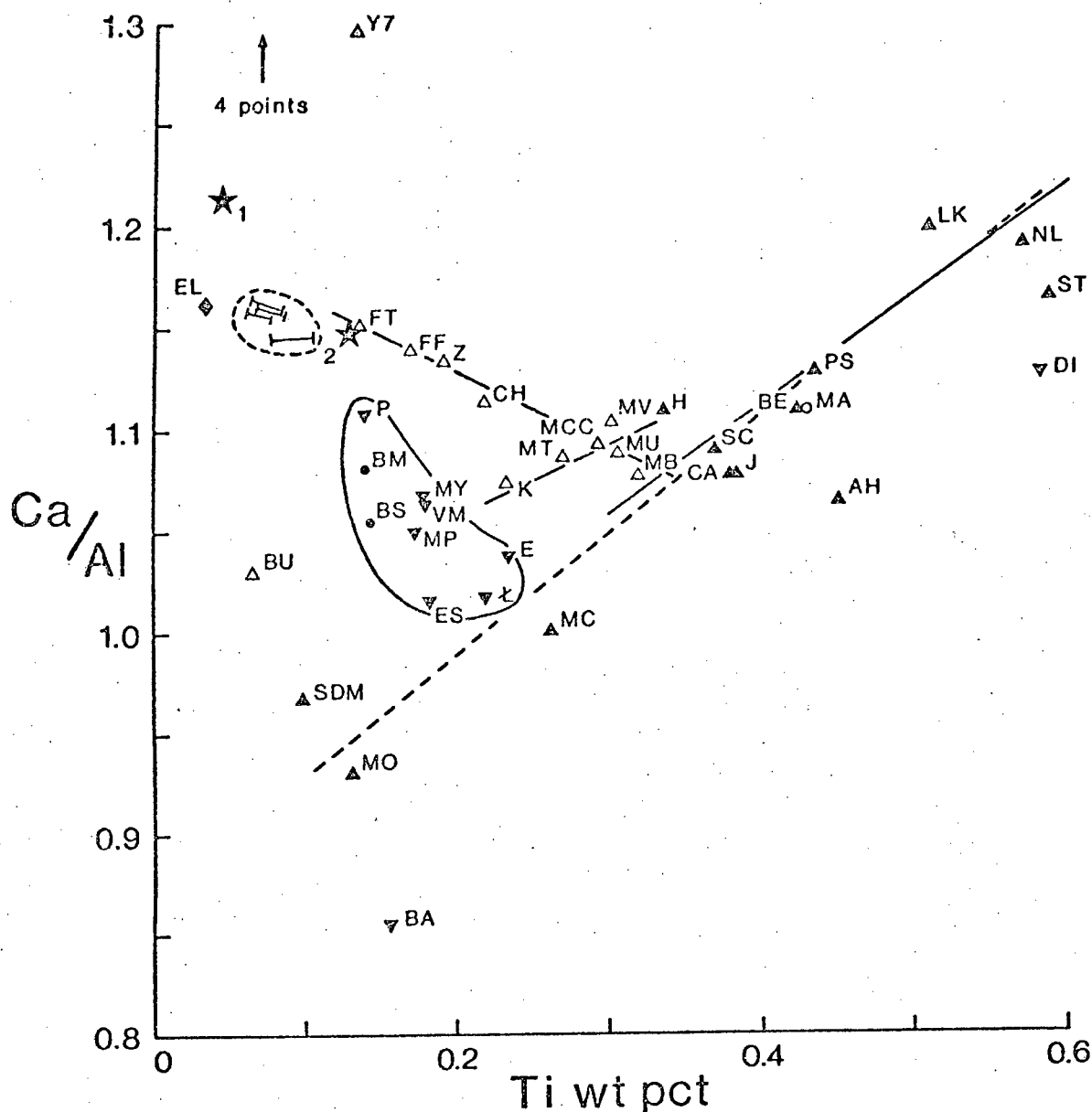


Fig. 5.20. The relationship between the Ca/Al ratio and Ti in the meteorites studied shows a clear distinction between the eucrite differentiation series (indicated by the interrupted regression line), the remaining achondrites, and the mesosiderites. The solid line through the 'primary' eucrites and the liquids differentiated from them was taken from STOLPER (1977a), Fig. 11. The mesosiderite field is outlined with a solid line, and includes the Binda analyses. The two source region compositions suggested by STOLPER (1977a) are indicated by solid stars with numbers. The field delimited by an interrupted line is that of possible compositions residual after the partial melting of Source Region 2 to produce the 'primary' eucrites. The bars within this field show the compositional ranges appropriate to Sioux County, Juvinas, Stannern, and Haraiya.

this calculated trend; the fit would be even better were Serra de Magé to have the higher content of Ti shown to be required by other plotted relationships. Stannern plots neither on Stolper's trend nor on that of the present work. This is in keeping with Stolper's conclusion that Stannern and Ibitira (not included in the present investigation) were not derived from 'primary' eucritic melts by low pressure fractionation in a way similar to most eucrites, but were produced by small degrees of melting of the source region. The interrupted trend line in Fig. 5.20 presumably connects members of a differentiation series, comprising the 'primary' melts, eucrites (some of them Fe-rich) fractionated from them, and the cumulate eucrites, products of crystal accumulation that took place during the fractionation processes; this is fully discussed in Chap. 8.

The possible course of evolution of the other achondrites plotted is less easy to understand. The data for most of the diogenites are not sufficiently accurate to establish their position on the plot; presumably they should fall in the vicinity of the point representing Ellement, approximately in line with the regression trend calculated for most of the howardites. This trend diverges from that of the eucrites at about the position occupied by the 'primary' eucrites, e.g. Juvinas and Sioux County. The howardites comprising this trend show an inverse correlation between the Ca/Al ratio and Ti concentration. However, not all the howardites plot on or near the regression line. Bununu and Yamato 7308 have been designated as unreliable for the purposes of this particular relationship, but no such objection applies to Kapoeta and Molteno, neither of which plots on the howardite trend. In Fig. 5.20, a tentative trend line was calculated for these two meteorites and three analyses of Malvern, but probably has no genetic significance. The eucrite Haraiya, which plots impeccably in other relationships involving Ca, Al, and Ti, lies approximately on this probably

spurious trend, well away from the 'primary' eucrites with which it is normally associated. The reason for Haraiya's anomalous behaviour in this plot is considered later in this section.

The mesosiderites analyzed in the course of the present study occupy an elongate field lying on the low-Ti side of the howardite trend at a high angle to the line of the eucrite differentiation series. The two analyses of Binda plot within this small field. The points representing Barea and Dyarrl Island are completely aberrant for reasons specified earlier in this section. No regression line could be drawn that would adequately represent the distribution of the mesosiderites in this relationship.

Interpretation of the inter-relations depicted in Fig. 5.20 is complex. The increase in the Ca/Al ratio with increasing low pressure fractionation, as indicated by the concentration of Ti, from the 'primary' eucrites to Fe-rich differentiates such as Nuevo Laredo is normal in a system in which the fractionating phases are magnesian pyroxene (pigeonite) and plagioclase. STOLPER (1977a) cited this positive correlation as confirmation of his experimental conclusion that augite was not a primary liquidus phase in the crystallization sequence of eucrites. The petrographic studies described in Chap. 3 of this work support this view; virtually no Ca-rich pyroxene was observed other than the volumetrically minor amounts produced by exsolution during inversion of pigeonite. The cumulate rocks produced by settling and accumulation of the fractionating phases (pigeonite and plagioclase) would be expected to lie on the same differentiation trend, and Fig. 5.20 shows this to be so, within the limits of the accuracy of the data.

The pronounced angular divergence between the eucrite trend and that of the more magnesian achondrites suggests a marked difference in genetic processes. The relationship between the trends is of the same general form as that seen in many of the element-element plots presented

earlier in this chapter, but is inverted. It is noteworthy that in these earlier plots, as in Fig. 5.20, the howardites plot on a line joining the diogenites with that part of the eucrite trend occupied by the 'primary' eucrites. This is somewhat surprising and difficult to account for if one accepts the ample evidence presented in this work and elsewhere for the existence of a eucrite differentiation series as opposed to a class of achondrites with tightly restricted chemical characteristics. The mixing hypothesis for the formation of howardites advocated mixing of this restricted class with the equally restricted diogenites (JÉROME and GOLES, 1971). The establishment of the eucrites as a series of compositionally diverse differentiated rocks implies that mixing would generate not a single mixing line, but a 'family' of such lines, on which the howardites would plot. That this does not occur is evident from the many inter-element relationships presented in this chapter. On the contrary, the ease with which well-fitting regression lines can be calculated for the howardites in all these relationships is noteworthy.

Acceptance of the STOLPER (1977a) hypothesis that the eucrites represent the earliest partial melts of the achondritic source region, and that the magnesian materials in diogenites and howardites were formed from the residues of this partial melting sequence after exhaustion of plagioclase, implies that the eucrites were in existence prior to the formation of the diogenites and were therefore available, as a series, for mixing. Unfortunately, radiometric dating sheds little light on the relative ages of these two classes of achondrites. The eucrites have been extensively studied. For instance, BIRCK and ALLÈGRE (1978a) determined the age of the differentiation of the eucrites as $4.57 \pm 0.13 \times 10^9$ years, using the ^{87}Rb - ^{87}Sr method, i.e. very early in the history of the achondrite parent body. However, the same authors (1978b) found the distribution of Rb and Sr to be

very heterogeneous in the diogenites, and observed that the points representing these meteorites were scattered around the 4.6×10^9 years reference isochron.

It must be accepted, therefore, that age determinations carried out on diogenites are not yet sufficiently exact to establish the time of their formation relative to that of the eucrites. However, if one assumes that the eucrite differentiation series existed by the time that the postulated mixing with the diogenites took place, then it becomes necessary to conclude that only a small part of the eucrite range was involved in this mixing because of the lack of evidence for a fan-like distribution of mixing lines linking the eucrite series with the diogenites. This is possible if, for instance, members of the series compositionally similar to the 'primary' melts were far more abundant, or better exposed at the surface of the parent body, than eucrites produced by higher degrees of fractionation or by accumulation. The existence of a restricted 'family' of mixing lines might account for the observation (Fig. 5.20) that Kapoeta, Molteno, and possibly Haraiya, do not plot in their expected positions. The possibility that these seemingly aberrant points may lie on other mixing lines was therefore investigated.

LANGMUIR et al. (1978) developed a general equation to describe the mixing process in two-component systems, with particular reference to clarifying mixing in ratio-ratio and ratio-element plots. They showed that, in the general case, the mixing line is a hyperbola of the form:

$$Ax + Bxy + Cy + D = 0$$

where A, B, C, and D are coefficients calculated from the x and y co-ordinates of two representative data points and from their denominators, if they are ratios. In element-element plots, such as those considered earlier in this chapter, the denominators are unity and the mixing curve reduces to a straight line. Use of the equation can test for mixing and can constrain the composi-

tions of the end-members if mixing has taken place. In the present instance, where a ratio (Ca/Al) is plotted against an element (Ti), hyperbolic mixing curves might be expected. Inspection of Fig. 5.20 shows that a linear regression can be established for most of the howarditic compositions under consideration, as already noted. This suggests that the relationship is not that of mixing. This observation applies also to the succeeding two plots (Figs 5.21 and 5.22), in which the Ca/Al ratio is plotted against Zr and the $\text{Fe}/\text{Fe}+\text{Mg}$ ratio. Nevertheless, an attempt was made to calculate mixing curves that might include possible eucritic end-members and one or other of the points that do not lie on the howardite line in Fig. 5.20. No success was achieved, and it was therefore concluded that the trend defined by the howardites in Figs 5.20 - 5.22 is unlikely to be a mixing line.

If the trend that is clearly defined by the howardites in all the inter-element relationships examined in this chapter did not arise from mixing of eucritic and diogenitic end-members, an alternative mechanism for its formation must be found. STOLPER (1977a) proposed that the Mg-rich pyroxenes present in howardites, diogenites, and mesosiderites could have originated from further partial melting of the residues left in the source region after exhaustion of plagioclase in the production of 'primary' eucritic liquids. Using the conclusions of PRESNALL (1969) on the differences between equilibrium and fractional fusion, Stolper showed that further heating of these plagioclase-depleted residues would, under conditions of equilibrium fusion or imperfect fractional fusion, produce melts with compositions plotting along the olivine-pyroxene boundary curve of the silica-olivine-anorthite 'pseudo-ternary' phase diagram on which he projected his experimental data (STOLPER, 1977a, Figs 5 and 8). The $\text{Fe}/\text{Fe}+\text{Mg}$ ratios of these melts would decrease with increasing degrees of partial melting of the residues in the source region. Later in this chapter, when this topic is

more fully discussed (section 5.10.2), it will be shown that the howardites investigated are situated on the liquid path of these partial melts. This observation strengthens the suggestion made by several writers (e.g. REID, 1974; SIMPSON, 1974, 1975; BUNCH, 1975; and DYMEK et al., 1976) that the materials from which howardites were derived represent an essentially continuous compositional series produced by igneous processes, in this instance increasing degrees of partial melting. Such continuity of liquid descent could also be attained, however, by fractional crystallization (PRESNALL, 1969).

At this point, it is appropriate to examine the nature of the residues remaining in the source region after the small degrees of partial melting that produced the 'primary' eucrites. The experimental data of STOLPER (1977a) suggested that eucrites were generated from a single source region in which the five liquidus phases - olivine (about Fo_{65}), pyroxene (about $\text{Wo}_5\text{En}_{65}$), plagioclase (about An_{94}), Cr-rich spinel, and metal estimated to contain 6-8% Ni and 0.5% Co - were present. Although eucritic liquids could be produced by low pressure partial melting of any mixture of these phases, Stolper was able to constrain the permissible compositions by petrological and geochemical considerations, including the Ca/Al ratio. He presented two estimates, referred to here as Source Region 1 and Source Region 2 respectively; both were based on the compositions of the experimentally-produced liquidus phases. The first was composed of approximately 65% olivine, 30% pyroxene, 5% plagioclase, and negligible spinel, the second of 90% pyroxene, 5% plagioclase, and 5% spinel, with negligible olivine. Averaged data from Stolper's Table 2 have been used to calculate the bulk compositions of the two suggested source regions (Table 5.8).

Stolper does not specify the role of metal in these possible source regions. Presumably metal was either present in negligible amounts, or

Table 5.8. Averaged compositions of experimentally-produced phases in Juvinas and Sioux County (original data from Stolper, 1977a, Table 2), and compositions of two possible source regions of eucritic liquids calculated from alternative proportions of these phases suggested in the same work

	Olivine	Plagio- clase	Clino- pyroxene	Spinel	Source region 1	Source region 2
SiO ₂	36.82	45.36	53.24	1.06	42.02	50.24
TiO ₂	0.04	0.01	0.15	1.61	0.07	0.22
Al ₂ O ₃	0.11	33.86	1.13	18.80	2.10	3.65
Cr ₂ O ₃	0.30	0.01	0.69	42.35	0.40	2.74
FeO*	31.00	0.99	19.05	27.38	25.82	18.56
MnO	0.74	0.05	0.71	0.63	0.70	0.67
MgO	31.11	0.17	22.72	6.30	26.95	20.77
CaO	0.38	18.54	2.39	0.43	1.88	3.10
Na ₂ O	0.02	0.70	0.02	0.01	0.05	0.05
TOTAL	100.52	99.69	100.10	98.57	99.99	100.00
Ca/Al (wt)	---	---	---	---	1.213	1.147
Fe/Fe+Mg (molar)	0.359	---	0.320	---	0.350	0.334

Notes: 1. The mineral assemblage in Source Region 1 is given as approximately 5% plagioclase, 30% pyroxene, 65% olivine, and a negligible amount of spinel (Stolper, 1977a).

2. Source Region 2 consists of 5% plagioclase, 90% pyroxene, 5% spinel, and negligible olivine.

played only a minor part in the limited partial melting that generated the 'primary' eucrites. If the former alternative applied, it would conform with the suggested origin of achondritic source material by oxidation of the metal of the 'main trend' mesosiderites (sections 5.3.2 and 5.3.3). Even if the eucritic melts were metal-saturated, as suggested by the experimental results, arguments advanced by Stolper (pp. 596-597) show that metal is unlikely to crystallize from these melts until very late in the crystallization sequence, possibly because of metal-silicate reaction near liquidus temperatures. It is interesting to note that the composition of the metal phase in equilibrium with eucritic melts at their liquidi, as calculated by Stolper, is similar to the metal of mesosiderites or pallasites, and caused him to comment (p. 605): "This is consistent with an indigenous origin of the metal in mesosiderites and it may suggest that this metal played an important role in the genesis of magmas on the basaltic achondrite parent body." This speculative comment hints at the hypothesis of origin of achondritic source material presented earlier in this chapter. Stolper did not, however, consider the presence of metal-rich meteorite material in the basaltic achondrite parent body as necessarily indicative of source regions that were metal-rich because the metal could have been concentrated by secondary processes such as sinking and coalescence.

Points representing Source Regions 1 and 2 have been plotted in Fig. 5.20 using the actual Ca/Al ratios calculated from the data of Table 5.8. STOLPER (1977a) estimated that Sioux County and Juvinas had been formed by about 15-20% partial melting of the source region, and Stannern by about 5-10%. The compositional ranges of the residues corresponding to these degrees of partial melting can be represented graphically on a basis of proportionality, and this has been done for Source Region 2 in Fig. 5.20, defining an area in which the compositions of the residues probably lie.

The corresponding area for Source Region 1 falls beyond the limits of the plot, suggesting that this source composition may not be genetically feasible. As will be shown later, other plots confirm this observation.

In Fig. 5.20 (and some of the plots that follow), Haraiya does not lie on the main eucrite trend. STOLPER (1977a), arguing from the premise that Zr and U are perfectly incompatible elements, suggested that the composition of Haraiya resulted from minor fractionation of a liquid generated by a higher degree of partial melting than that of Sioux County (see his Fig. 9), which he estimated at 15-20%. The Zr data in Table 4.19 indicate that about 20-25% melting could have been involved in the formation of Haraiya, assuming the subsequent fractionation to have been relatively minor. This range was used in Fig. 5.20, and gave residual compositions that plot within the area defined by the residues calculated from Stannern, Sioux County, and Juvinas.

5.5.2 The relationship between the Ca/Al ratio and Zr

In order to check the validity of the relationships observed in Fig. 5.20, the Ca/Al ratios of the meteorites studied were plotted against other measures of igneous differentiation. The first of these was the incompatible trace element Zr (Fig. 5.21). This plot shows the same general trends as the Ca/Al-Ti relationship, although data on Zr are limited. Kapoeta and Haraiya again plot away from the howardite and eucrite trends respectively, and the analyses of Binda again fall within the mesosiderite field. No estimations of the compositions of possible residues from eucrite partial melting processes could be made in this instance because the compositions of the two suggested source regions are too approximate to include data on trace elements.

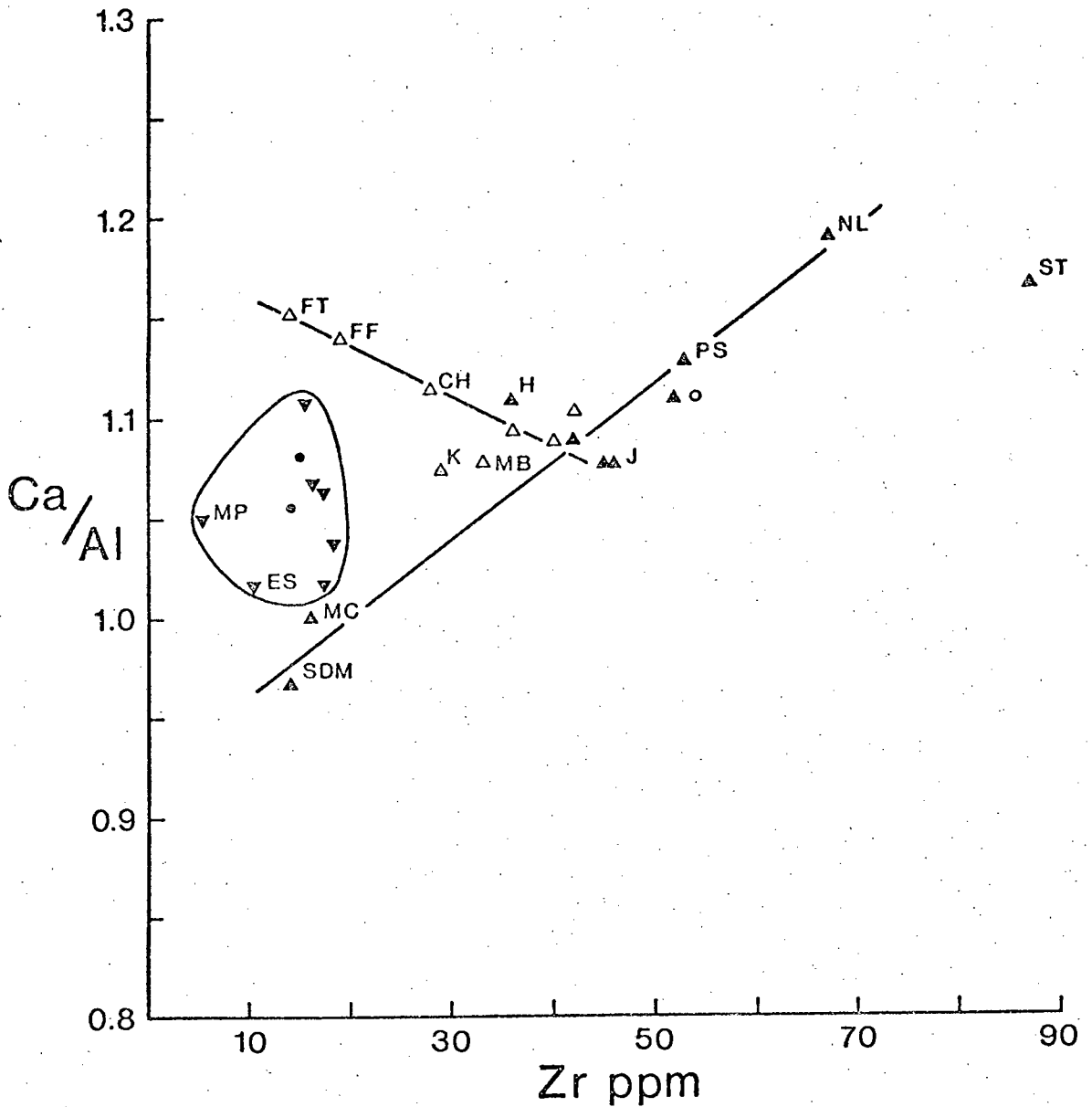


Fig. 5.21. The relationship between the Ca/Al ratio and the incompatible trace element Zr, used as a measure of differentiation. The plot confirms the distribution of the various classes of meteorites established in Fig. 5.20. Kapoeta and Haraiya plot anomalously, as in the previous diagram. The mesosiderites plot in a field apparently unrelated to either of the achondrite trends; the Binda analyses fall in that field, as in other relationships. The positions of the estimated compositions of Source Regions 1 and 2 could not be plotted in this figure.

5.5.3 The relationship between the Ca/Al and Fe/Fe+Mg ratios

The next parameter of differentiation to be plotted against the Ca/Al ratio was the molar Fe/Fe+Mg ratio (Fig. 5.22). The values of this frequently-used ratio for the meteorites under consideration are listed for convenience in Table 5.9. Complete data are available for this ratio-ratio plot, but the limitations on the quality of the Ca/Al values for certain meteorites noted at the start of section 5.5.1 must be kept in mind. The plot shows the same arrangement of trends as seen in Figs 5.20 and 5.21, with minor differences. Haraiya falls on the eucrite line, but Macibini occupies a position intermediate between that line and the howardite trend. Kapoeta and Molteno plot in positions corresponding to those in Fig. 5.20, again suggesting a subsidiary trend on which, in this instance, Macibini may fall. If such a trend is real, the reason for its existence is not understood. The two Binda analyses plot close to this trend, which is tentatively indicated in Fig. 22, but they might be considered also as falling within the mesosiderite field.

Points representing the compositions of Source Regions 1 and 2, and the compositional fields of possible residues remaining after formation of the 'primary' eucrites, were plotted on this diagram as previously described. The field derived from Source Region 1 bears no clear relationship to any of the meteorite trends or groupings, but that calculated from the alternative source composition occupies a position analogous to that observed in the Ca/Al versus Ti plot, i.e. roughly between the most magnesian howardites and the diogenite Ellement. This close relationship to recognized classes of achondrites strengthens the credibility of this composition estimated on the basis of a negligible content of olivine in the source region.

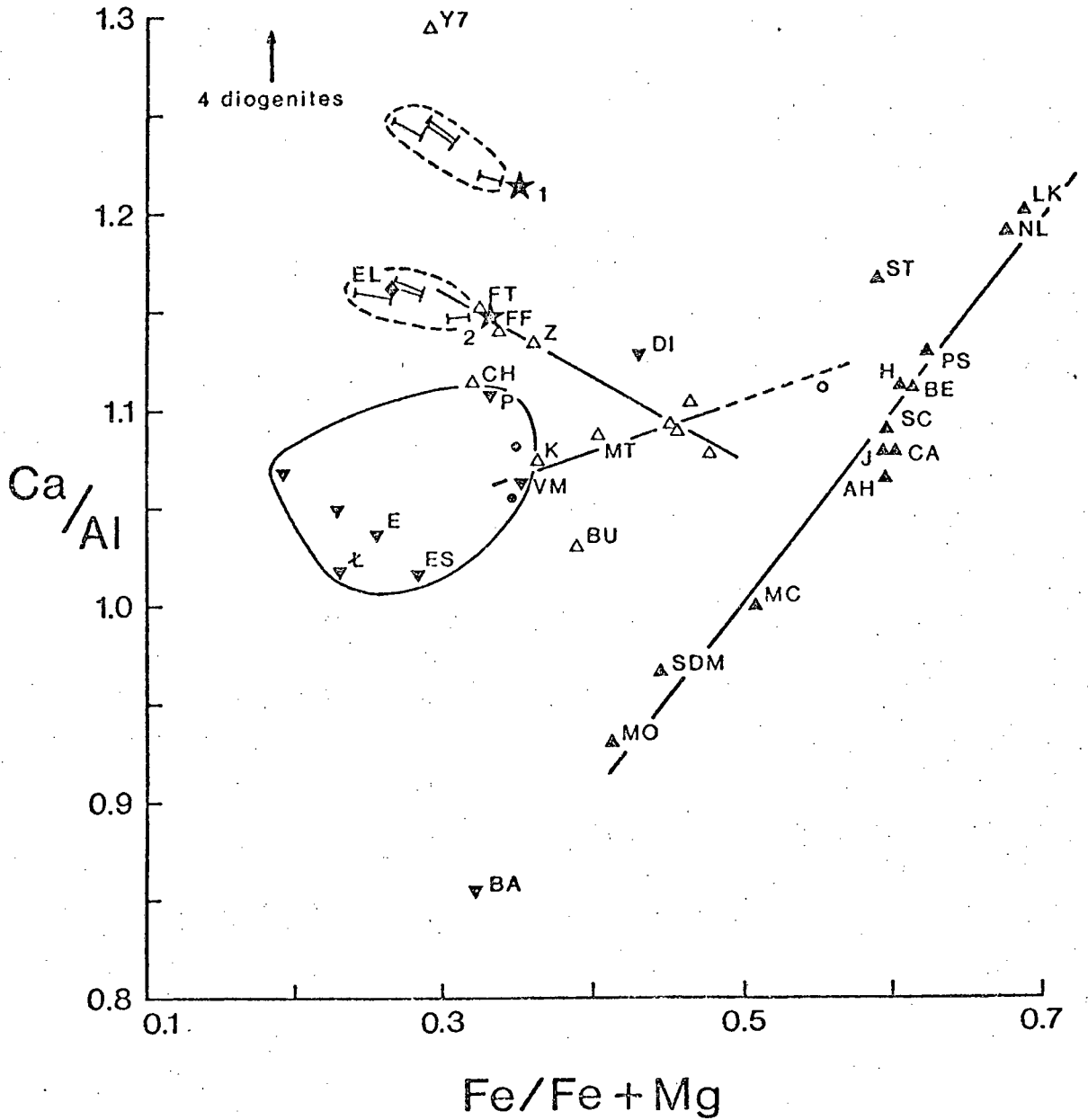


Fig. 5.22. The relationship between the Ca/Al (weight) ratio and the $\text{Fe}/\text{Fe} + \text{Mg}$ (molar) ratio in the meteorites investigated. The trends and groupings seen in the two preceding figures are again evident in this plot. A subsidiary trend involving Kapoeta, Molteno, some of the Malvern analyses, and possibly Macibini is tentatively drawn. Binda plots in the mesosiderite field (demarcated by a solid line), but lies close to the subsidiary trend. Haraiya plots on the main eucrite regression line in this figure. The compositions of Source Regions 1 and 2 are indicated by solid stars, and the fields of possible residual compositions associated with them are enclosed by interrupted lines, as in Fig. 5.20.

Table 5.9. Fe/Fe+Mg (molar) ratios in the meteorites included in this investigation

METEORITE	Fe/Fe+Mg (molar)	METEORITE	Fe/Fe+Mg (molar)
<u>Table 4.2</u>		Moama	0.412
Malvern (UCT)	0.455	Moore County	0.507
Malvern (BLM)	0.474	Nuevo Laredo	0.674
Binda	0.345	Pasamonte	0.621
Kapoeta	0.362	Serra de Magé	0.444
Molténo	0.402	Sioux County	0.595
<u>Table 4.4</u>		Stannern	0.588
Mincy	0.193	<u>Table 4.8</u>	
Patwar	0.333	Binda	0.347
Estherville	0.284	Bununu	0.388
Mount Padbury	0.228	Chaves	0.319
Vaca Muerta	0.352	Frankfort (F)	0.336
Emery	0.256	Frankfort (T)	0.324
Łowicz	0.231	Malvern	0.463
<u>Table 4.6</u>		Malvern	0.449
Vaca Muerta	0.343	Yamato 7308	0.290
Łowicz	0.221	Zmenj	0.359
<u>Table 4.7</u>		<u>Table 4.9</u>	
Allan Hills 7605	0.594	Ellemeet	0.265
Béréba	0.612	Johnstown	0.260
Cachari	0.600	Shalka	0.261
Haraiya	0.603	Tatahouine	0.231
Juvinas	0.593	Yamato 6902	0.212
Lakangaon	0.686	Barea	0.322
Macibini	0.551	Dyarri Island	0.430

5.6 RELATIONS INVOLVING THE Fe/Fe+Mg RATIO

5.6.1 The relationship between Ti and the Fe/Fe+Mg ratio

STOLPER (1977a, Fig. 9) studied the course of crystallization differentiation in the non-cumulate eucrites and the experimental liquids produced by the melting of Sioux County and Juvinas by plotting their Ti concentrations against molar Fe/Fe+Mg ratios, Ti being regarded as an incompatible element in fractionation processes involving magnesian pyroxene and plagioclase. The positive correlation established between these parameters was observed also in other incompatibles including the rare earth elements. SIMPSON and AHRENS (1979) extended this approach to the cumulate eucrites and the other achondrites and mesosiderites included in the present investigation. The result may be seen in Fig. 5.23, which shows that the cumulate eucrites also plot on the trend established for the non-cumulate varieties. As usual, Stannern does not lie on this liquid line of descent, and the position of Haraiya suggests that it too may have originated separately by partial melting, as noted above, and not by fractionation of a liquid similar to Sioux County or Juvinas. The howardites and diogenites define a differentiation trend clearly distinct from that of the eucrites. The position of Macibini on that trend, rather than on the eucrite line, was used by SIMPSON and AHRENS (1979) in support of other arguments for the re-classification of this polymict achondrite as a howardite; this topic is discussed in a later part of this chapter. The mesosiderite silicates plot in an elongate field that does not conform to either of the achondrite trends, and do not show enrichment in Ti with increase in the Fe/Fe+Mg ratio. This suggests a mode of origin different from the achondrites, not involving the same sequence of igneous events indicated by both eucritic and non-eucritic trend lines.

The existence of two distinct evolutionary trends in the achondrites in this and other relationships provides strong support for the conclusion of

Fig. 5.23. The relationship between Ti and the molar Fe/Fe+Mg ratio indicates differences in the modes of formation of the achondrites and mesosiderites. The eucrites appear to have been formed by crystallization differentiation from 'primary' melts such as Sioux County and Juvinas. Their evolution is represented by a solid regression line, calculated excluding Stannern. Howardites and diogenites may represent a similar series derived by partial melting and fractionation of the magnesian residues from eucrite genesis; this is indicated by the solid regression line that includes Macibini. The limits of the compositional field of these residues, calculated from Source Region 2, are marked by an interrupted line. Alternatively, the howardites may have been formed by mixing of these residues (or the diogenites) with the 'primary' eucrites. Two possible mixing lines have been calculated (see the text) and are shown as curved interrupted lines that merge in the vicinity of Molteno. The mesosiderites are contained within an elongate field (bounded by a solid line in the figure). They differ markedly from both groups of achondrites in showing no enrichment in the incompatible element Ti with increase in Fe/Fe+Mg ratio, and appear therefore to have been operated on by different processes during their formation. Note the close association of the Binda analyses with the mesosiderite field, and also the departure of the howardites Zmenj, Frankfort (F), and Frankfort (T) from the possible mixing lines. Non-standard abbreviations and symbols: MA- Macibini; YD - diogenite inclusion in Yamato 7308; circles - howardites, including Macibini; filled circles - mesosiderites; inverted triangles - diogenites analyzed in this laboratory; and upright triangles - other diogenite analyses.

STOLPER (1977a) that the achondrites were formed by partial melting of the source region in two separate stages, the break occurring at the point at which plagioclase was exhausted. Similarly, the plotting of inter-element relationships, including that of Fig. 5.23, has provided clear indications that the eucrites constitute a single differentiation series in which the 'primary' melts, the liquids fractionated from them, and the cumulate eucrites are all related in a simple fashion, contrary to the views of Stolper. The results of computer modelling (described in Chap. 8) support the idea of a simple relationship in the eucrites. A further point to emerge from Fig. 5.23 is that the howardite-diogenite trend, as represented in the figure, is unlikely to be a mixing line. It intersects the eucrite line only at a very high value of $\text{Fe}/\text{Fe}+\text{Mg}$ (approximately 0.8), beyond the range of known eucrites and even beyond the most Fe-rich liquids produced in the course of Stolper's experimental work. However, as discussed in section 5.5.1, mixing lines in plots involving ratios generally take the form of hyperbolic curves (LANGMUIR et al., 1978). Such curves may be calculated from any two representative data points. This was tested for the Ti versus $\text{Fe}/\text{Fe}+\text{Mg}$ relationship using two pairs of howardites: (1) Kapoeta and Malvern (BLM), and (2) Yamato 7308 and Malvern (UCT). The observed and calculated data for these pairs are set out in Table 5.10, which shows convergence of the two sets of co-ordinates at an $\text{Fe}/\text{Fe}+\text{Mg}$ ratio of about 0.4. Plotting of the two curves in Fig. 5.23 confirms this, and shows that they pass through the 'primary' eucrites, most of the howardites, and the part of the plot occupied by the diogenites and the compositional field of possible residues left after extraction of the 'primary' eucritic melts from Source Region 2 (Source Region 1 has again to be discounted, because the residues calculated from it do not lie within the limits of the plot). The maximum divergence of the two curves occurs in this low-Ti, high-Mg region, creating more doubt over

the possible composition of the magnesian member of the mixing series than exists at the eucritic end.

The existence of these two very similar mixing curves that pass through eucritic and diogenitic compositions considered as the end-members in a binary mixing process that produced the howardites (e.g. JÉROME and GOLES, 1971) is somewhat confusing in view of the evidence that has accumulated against such simple two-component mixing. Nevertheless, the close correspondence between the parameters defining the two curves (Table 5.10) shows that the relationship is not merely fortuitous for the Ti versus Fe/Fe+Mg plot. However, LANGMUIR et al. (1978) caution that calculated curves such as these do not in themselves constitute proof of mixing. Other criteria are that all data for samples considered to have been formed by mixing should conform to mixing curves when plotted, and that individual samples should maintain the same relationship to one another in all plots because this is determined by the degree of mixing of the end-members. If the diogenite-howardite trends in the element-element plots presented earlier in this chapter are mixing lines, these criteria are largely satisfied, but this may not be true of the ratio-element plots. As previously noted, mixing curves were not established for the Ca/Al versus Ti plot (Fig. 5.20), but it is interesting to note that the direction of the line linking the diogenite Ellemeet (and the possible residues from partial melting of Source Region 2) with the 'primary' eucritic melts is largely determined by the howardites Zmenj, Frankfort (F), and Frankfort (T), which do not lie on the mixing curves in Fig. 5.23. There are too few data on Zr for Fig. 5.21 to be of assistance in this respect, and the relationship between the Ca/Al and Fe/Fe+Mg ratios (Fig. 5.22) shows the same characteristics as Fig. 5.20, and is therefore similarly inconclusive. It is unfortunate that the Ca/Al ratio of Yamato 7308 is suspect, because the correct position of this Mg-rich

Table 5.10. Parameters for the two mixing lines drawn in Fig. 5.23 calculated from two pairs of howardites possibly formed by such mixing

Meteorite pairs	Coefficients of mixing equation				r $(\frac{a_1}{a_2})$	Ti (wt%)	Obs. and calc. Fe/Fe+Mg (molar)
	A	B	C	D			
Kapoeta)	0.023	0.099	-0.077	0.014	1.189	0.234*	0.362*
Malvern(BLM))						0.320*	0.474*
						0.05	0.212
						0.10	0.244
						0.20	0.327
						0.30	0.445
						0.35	0.525
						0.40	0.626
Yamato 7308)	0.020	0.242	-0.169	0.037	1.446	0.132*	0.290*
Malvern(UCT))						0.306*	0.455*
						0.05	0.243
						0.10	0.270
						0.20	0.341
						0.30	0.447
						0.35	0.524
						0.40	0.626

- Notes:
1. The coefficients A-D are calculated for the general mixing equation of Langmuir et al. (1978).
 2. The ratio r is a measure of the curvature of the mixing line.
 3. Observed values are distinguished by an asterisk.

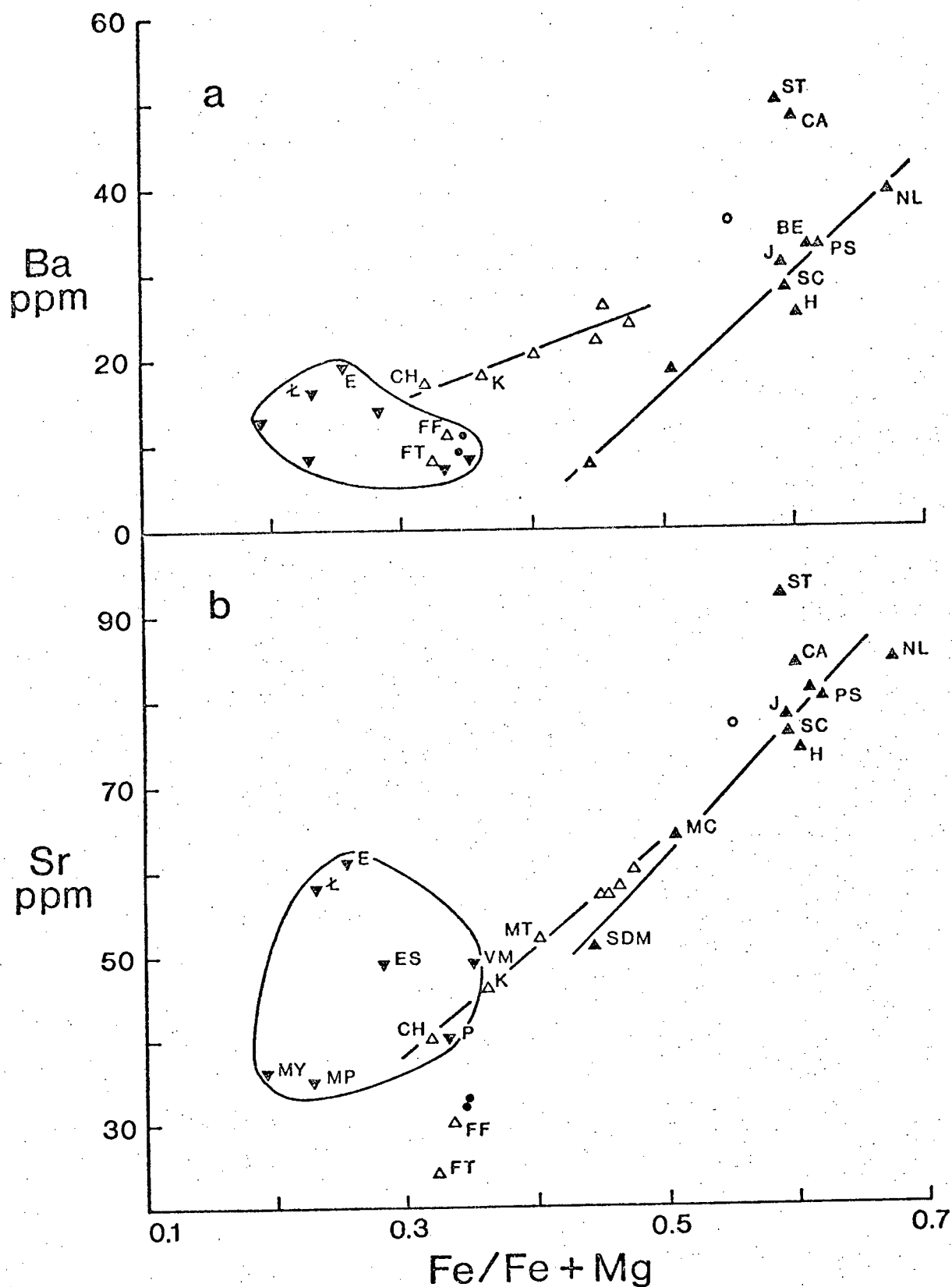


Fig. 5.24. The plots of the Fe/Fe+Mg ratio and the incompatible elements (a) Ba and (b) Sr show the same general characteristics as that for Ti (Fig. 5.23), but the howardites cannot easily be represented by single regression lines. Those drawn are tentative.

5.6.4 The relationship between Y and the Fe/Fe+Mg ratio

There are too few data on Y to define the eucrite series in this plot (Fig. 5.25a), but a trend line can be drawn for the howardites that, when extended, passes through Macibini. Concentrations are generally low, with Frankfort and Binda showing the lowest levels except for Estherville and Mount Padbury, in which the element was not detected (Table 4.4).

5.6.5 The relationship between Zr and the Fe/Fe+Mg ratio

The plot of these parameters (Fig. 5.25b) confirms the general relationships seen in the preceding figures, but the howardite trend is poorly established. The Frankfort and Binda samples again show concentrations of the incompatible element similar to those of the mesosiderites and, in this instance, lie within their field. The extreme enrichment of Stannern in Zr is noteworthy, exceeding that of the 'primary' eucrites by a factor of about two. This was interpreted by STOLPER (1977a) as indicative of a low degree of partial melting, and the proposed differences in partial melting between Stannern, the 'primary' melts, and Haraiya, as revealed by their contents of Zr, are clearly brought out in this plot (see section 5.5.1 and Fig. 5.20).

5.7 THE CLASSIFICATION OF BINDA

The classification of Binda has presented problems ever since distinctions were drawn between eucrites and howardites. The meteorite is clearly non-chondritic and appears to have chemical and mineralogical compositions similar to those of the howardites although its style of brecciation is different. DUKE and SILVER (1967) tentatively classed it as a eucrite, but were fully aware of its differences from other eucrites including the unbrecciated cumulates Moore County and Serra de Magé. They noted also that

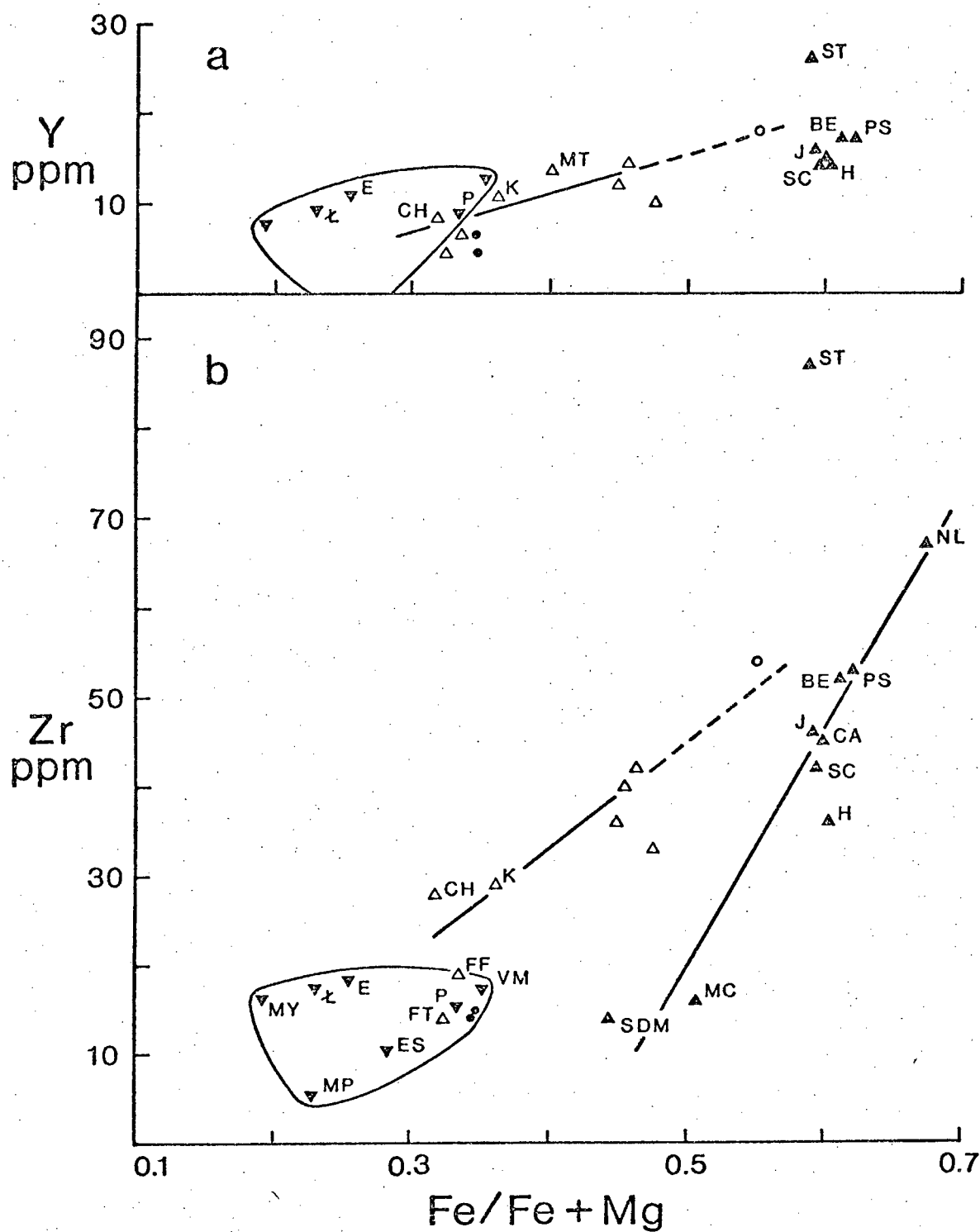


Fig. 5.25. The incompatible elements (a) Y and (b) Zr are plotted against the $\text{Fe}/(\text{Fe} + \text{Mg})$ ratio, confirming the general relationships of the previous figures. These plots do not clarify the mode of formation of the howardites because the data are inadequate to establish whether mixing took place or not.

"Binda is the only eucrite definitely within the pyroxene field" of their Fig. 16 (p. 1659), in which all howardites and mesosiderites for which data were available were plotted. Anomalous features such as these, together with the possibility expressed by McCARTHY et al. (1973) that Binda might represent a liquid from which the eucrites were derived, prompted its inclusion in the study reported in this work. The textural and mineralogical data presented in Chap. 3 support the view that the meteorite is a cumulate of orthopyroxene and plagioclase, now an essentially monomict breccia.

The cumulate character of Binda led STOLPER (1975) to suggest that it is a cumulate eucrite (cf. the views of DUKE and SILVER, 1967) and, as discussed in section 3.5.1, this 'classification' has been adopted - rather uncritically, in the opinion of the present writer - by other workers. The inter-element relationships studied in this chapter have indicated that this 'classification' is unlikely to be correct. This premise is discussed below and an alternative is proposed, but it should be noted that Binda's monomict brecciation, formerly regarded as the textural criterion by which eucrites could be distinguished from howardites, has lost much of its validity because of the recovery of eucrites exhibiting polymict brecciation from the Antarctic; monomict eucrites are in fact not common among the Antarctic samples (REID, 1982).

The plotting of the relationships between elements (and elemental ratios) carried out in this chapter has shown graphically that all the eucrites, whether 'primary' melts, differentiated liquids, or cumulates, can be considered as a related compositional series. Chap. 8 will attempt to prove this by means of computer modelling. In almost all of the preceding plots (Figs 5.1 - 5.25), the recognized cumulate eucrites - Moama, Moore County, and Serra de Magé - fall on or very close to the regression line calculated for the eucrites as a whole. Deviations from these calculated

trends are generally within the limits of the precisions estimated for the new analyses in this work (Tables A7.1 and A7.2) although many of the data were taken from the literature (Tables 4.7 and 4.19) and the remainder came from earlier analyses carried out in this laboratory. By contrast, as noted frequently in this chapter, the two analyses of Binda invariably do not plot on or even near the eucrite trend wherever it may be seen to be distinct from the trend of the other achondrites, i.e. in most of the relationships studied. Furthermore, the Binda analyses are generally far removed from the positions occupied by the cumulate eucrites in these plots, showing that there is little basic similarity in their chemical compositions; this may be confirmed from Tables 4.2, 4.7, 4.8, and 4.19. Significant differences exist also in the Ca/Al and Fe/Fe+Mg ratios and are clearly illustrated in Fig. 5.22.

It can therefore be concluded from the present work that Binda is compositionally different from the cumulate eucrites and does not appear to have evolved in the same way. It has also been found, by the present writer and by other workers, e.g. TAKEDA et al. (1976), that the compositions of pyroxenes in Binda are different from those in the cumulate eucrites. Evidence in support of this is presented in Chap. 7, in which the results of the electron microprobe studies are detailed. It has in addition been suggested above that the monomict character of the meteorite, which appears to be the only feature that might link it with the eucrites (though not necessarily with the cumulate eucrites, because these are unbrecciated: DUKE and SILVER, 1967; LOVERING, 1975), carries less significance now than formerly, since many achondrites of eucritic composition have been found to be polymict breccias. It is evident, therefore, that the 'classification' of Binda as a cumulate eucrite is incorrect.

The examination of the bulk chemical data that has been undertaken in this chapter has suggested an alternative classification more in accordance

with these data. Binda was originally classified as a howardite (HEY, 1966) presumably on account of the magnesian nature of its pyroxenes (ANDERSON and MINGAYE, 1913). The inter-element plots in this chapter show that the two analyses of the meteorite do, in some instances, fall on or close to the trend defined by the howardites and diogenites. However, closer examination reveals that this may be coincidental because, in such cases, the mesosiderite field or trend crosses the howardite trend, generally in the vicinity of the points representing the analyses of the two samples of Frankfort and the association of Binda is not with the howardites but with the mesosiderites. This is evident in relationships in which the distributions of achondrites and mesosiderites are distinct from one another, e.g. Ca/Ti (Fig. 5.2); Sr/Zr (Fig. 5.5); and Ca/Al versus Zr (Fig. 5.21), and attention has been drawn to this association throughout the entire series of inter-element relationships. It has also been pointed out that wherever it has been possible to calculate regression lines for the mesosiderites, the Binda analyses plot on, or close to, these lines in spite of having been excluded from the regression calculations.

The chemical evidence from the present investigation appears, therefore, to indicate a similarity between Binda and the silicate fractions of the mesosiderites. Early in the investigation it was realized that the general level of trace element concentrations is lower in Binda than in the four samples of acceptably-classified howardites analyzed at the same time (Table 4.2). This observation applies also to the trace element data published for the howardites and eucrites included in the investigation (Table 4.19). The only exceptions are the samples of Frankfort which, as illustrated by the inter-element plots in this chapter, bear a general compositional resemblance to Binda but are not identical to it in all respects. The cumulate eucrites Moore County and Serra de Magé contain almost twice the

concentration of Sr present in Binda although their contents of Ba and Zr are similar (Tables 4.2 and 4.19). The trace element concentrations in Binda are more closely comparable to those of certain of the mesosiderites, e.g. Patwar (Table 4.4). Other trace element data that underline the lack of similarity between Binda and the howardites are reported by CHOU et al. (1976, p. 3515), who found that the siderophile element pattern in a sample of Binda was "strikingly different" from those of the howardites they examined.

If, as the chemical evidence suggests, Binda is composed of material similar to the silicates of mesosiderites, it must be regarded as a segregation (or part of a segregation) of silicate minerals and opaques with a minimum mass of about 5.4 kg (HEY, 1966) that was ejected from a brecciated mesosideritic source area. The virtual absence of metal from the meteorite supports this concept of segregation and, if earlier reasoning that the phosphate minerals of mesosiderites were produced by reaction at metal-silicate boundaries (section 5.3.3) is correct, suggests an explanation for the very low content of P_2O_5 in Binda (Table 4.2); phosphates concentrated along metal-silicate boundaries might reasonably be expected to be absent from silicate masses that are devoid of metal.

Testing of the re-classification of Binda suggested on the basis of bulk chemical considerations by comparison of the meteorite's mineralogical and petrographic characteristics with those of the howardites, the cumulate eucrites, and the mesosiderites is obviously essential, but will be deferred till Chap. 7, when compositional data on the constituents of Binda and four howardites will be discussed. The mineralogy and petrography of the cumulate eucrites and the mesosiderites fall outside the scope of the present study. As a result, data from recent publications will have to be used to test Binda's correspondence with these meteorite classes.

The effects of forcing Binda into classification as a eucrite against the evidence afforded by its bulk chemical composition is well illustrated by a recent publication on planetary basalts (BENCE et al., 1980). These authors, who used (prior to its publication) a compilation of data on meteoritic basalts by REID and DUKE (1981), confuse the issue by failing to distinguish between cumulate and non-cumulate eucrites while professing to be concerned only with primary, non-cumulate basalts. This does not, however, materially affect the present argument, which hinges on their treatment of Binda as a eucrite in a series of plots of inter-element relationships in extra-terrestrial basalts.

In their study of the elemental characteristics of various groups of planetary basalts, Bence and his colleagues used the 'Mg number' (the molar $\text{Mg}/\text{Mg}+\text{Fe}^{2+}$ ratio) as an indicator of igneous processes against which oxide or element concentrations could be plotted in order to illustrate differences between these groups. The 'Mg number' is, of course, the inverse of the $\text{Fe}/\text{Fe}+\text{Mg}$ ratio listed for the meteorites of the present study in Table 5.9. For convenience in the study of the following diagrams, the 'Mg numbers' of these meteorites are set out in Table 5.11. Some of the inter-element relationships included in the paper of Bence and his co-workers are featured in Figs 5.26 and 5.27, but these are plotted using the data of the present investigation.

Although Bence and his collaborators did not plot individual points in their diagrams, the position of Binda in the eucrite field is easily identifiable because of its high Mg number (0.65: Table 5.11). The most extreme example of the distortion of the eucrite field resulting from the inclusion of Binda is to be found in the plot of the Mg number against Al_2O_3 (Fig. 2a, BENCE et al., 1980). The corresponding plot of the data of this investigation is Fig. 5.26a, in which the Binda analyses are situated close to the

Table 5.11. Mg/Mg+Fe (molar) ratios in the meteorites included in this investigation

METEORITE	Mg/Mg+Fe (molar)	METEORITE	Mg/Mg+Fe (molar)
<u>Table 4.2</u>		Moama	0.588
Malvern (UCT)	0.545	Moore County	0.493
Malvern (BLM)	0.526	Nuevo Laredo	0.326
Binda	0.655	Pasamonte	0.379
Kapoeta	0.638	Serra de Magé	0.556
Molteno	0.598	Sioux County	0.405
<u>Table 4.4</u>		Stannern	0.412
Mincy	0.807	<u>Table 4.8</u>	
Patwar	0.667	Binda	0.653
Estherville	0.716	Bununu	0.612
Mount Padbury	0.772	Chaves	0.681
Vaca Muerta	0.648	Frankfort (F)	0.664
Emery	0.744	Frankfort (T)	0.676
Łowicz	0.769	Malvern	0.537
<u>Table 4.6</u>		Malvern	0.551
Vaca Muerta	0.657	Yamato 7308	0.710
Łowicz	0.779	Zmenj	0.641
<u>Table 4.7</u>		<u>Table 4.9</u>	
Allan Hills 7605	0.406	Ellemeet	0.735
Béréba	0.388	Johnstown	0.740
Cachari	0.400	Shalka	0.739
Haraiya	0.397	Tatahouine	0.769
Juvinas	0.407	Yamato 6902	0.788
Lakangaon	0.314	Barea	0.678
Macibini	0.449	Dyarrl Island	0.570

mesosiderite field but far distant from the well-defined eucrite differentiation trend. In addition, this plot illustrates a feature noted previously in relationships involving element ratios - the failure of the howardites to lie on a single regression line possibly because, as discussed for the Ti versus Fe/Fe+Mg plot (Fig. 5.23), the relationship is that of mixing of diagenitic and primary eucritic material, causing the howardites to plot on a curved mixing line (or lines). This possibility is not evident in the Mg/Al relationship (Fig. 5.16).

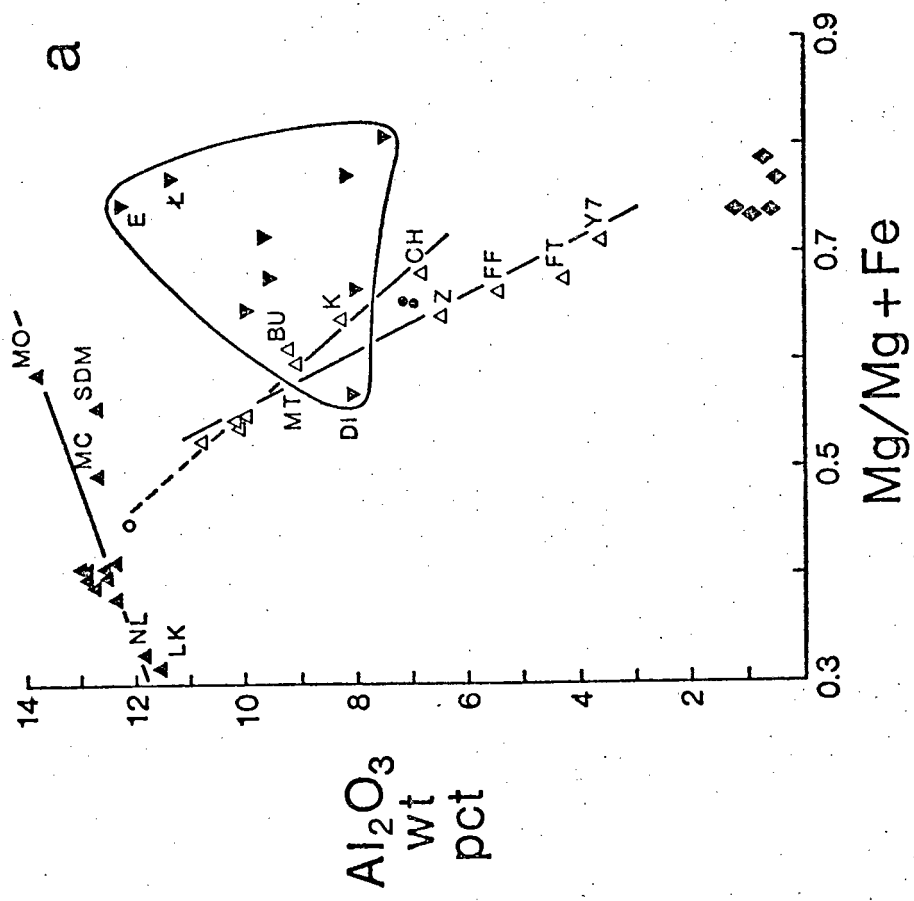
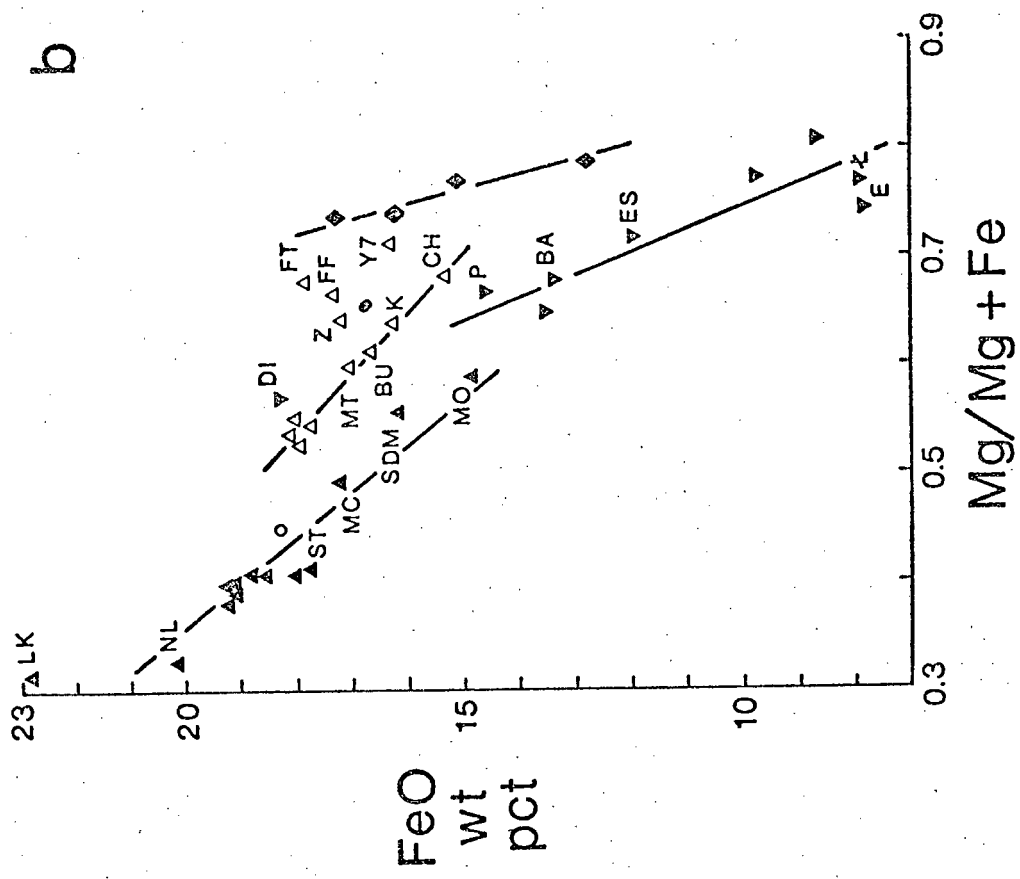
In the FeO versus Mg/Mg+Fe relationship (Fig. 5.26b), the eucrites lie on a clearly-established differentiation trend, but in the Bence equivalent (Fig. 4a) the eucrite distribution is again distorted by Binda, though to a lesser degree than in the previous plot. Fig. 5.26b shows also that a single regression line can be drawn for all the mesosiderites and that a lack of cohesion is present in the more magnesian howardites.

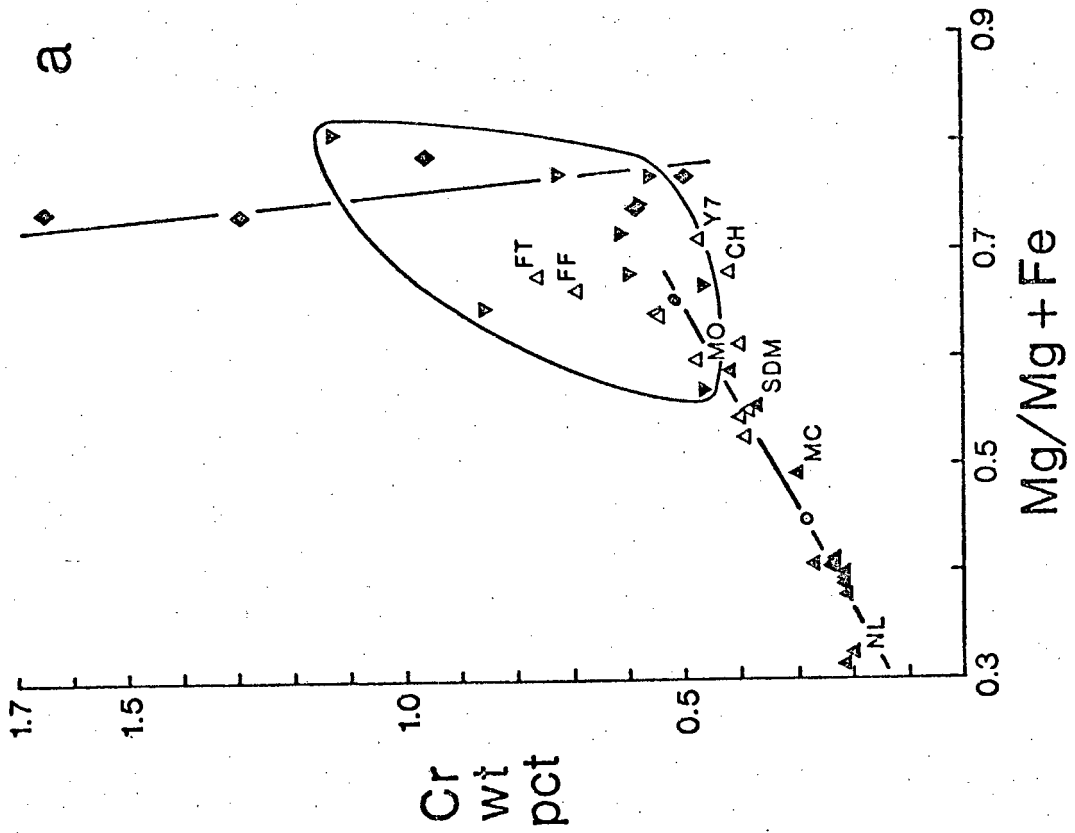
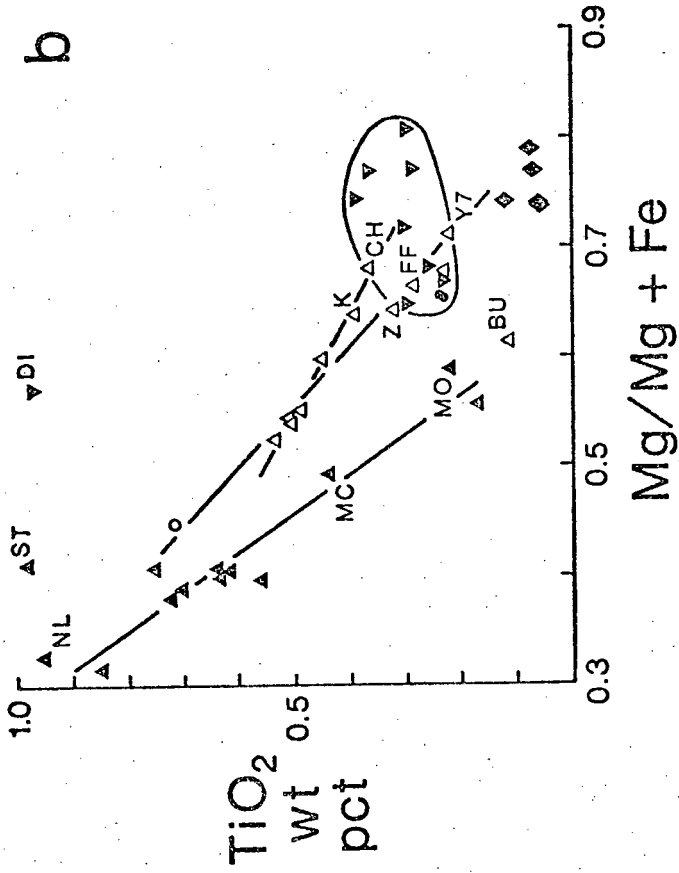
The relationship between Cr and the Mg number in the data of the present study (Fig. 5.27a) is similar to the Mg-Cr plot previously discussed (Fig. 5.19). Classification of Binda as a eucrite would extend the eucrite differentiation trend beyond the field occupied by the cumulates Moore County, Serra de Magé, and Moama. In the corresponding plot in the Bence paper (Fig. 7), the cumulate eucrites and Binda have been omitted. Had they been plotted, the eucrite field would have been extended to almost four times the length depicted.

In the plot of the relationship between TiO_2 and the Mg number (Fig. 1a in the Bence paper), Binda again elongates the eucrite field towards higher magnesian values. Fig. 27b presents this relationship for the current data in a considerably enlarged form of the Bence diagram. The plot is the converse of the Ti versus Fe/Fe+Mg plot already considered (Fig. 5.23). In both plots, the Binda analyses are well removed from the eucrite differen-

Fig. 5.26a. The relationship between the concentration of Al_2O_3 and the molar ratio $\text{Mg}/\text{Mg}+\text{Fe}$ (the 'Mg number') in the meteorites included in the present study, for comparison with Fig. 2a of BENCE *et al.* (1980). Note the position of the two analyses of Binda in relation to the three cumulate eucrites plotted and to the field (outlined) of the mesosiderites. As discussed in the text, the eucrites plot on a well-defined trend, but no single regression line can be drawn that includes the howardites and diogenites. Macibini does not lie on the eucrite trend, but may be related to some of the howardites by igneous processes rather than by mixing; it plots close to the extension of the regression line calculated for the Malvern analyses, Molteno, Bununu, Kapoeta, and Chaves.

Fig. 5.26b. The relationship between FeO and the 'Mg number', for comparison with Fig. 4a of the Bence paper. Trends can be drawn for the eucrite series, the howardites specified in the caption above, all the mesosiderites, and the diogenites. The analyses of Binda plot in almost coincident positions between the howardite and diogenite trends, far removed from the field of the cumulate eucrites.





tiation trend and are associated either with the mesosiderites or the more magnesian compositions that may fall on curved mixing lines joining the diogenites and the primary eucrites.

The Bence paper contains other examples, not considered here, of the distorting effect that classifying Binda as a eucrite has on the distribution of the eucrites. Even if none of the other chemical evidence presented in this section were taken into consideration, the distortion of the 'eucrite' field in the plot of Al_2O_3 against the Mg number should provide reason enough for questioning the logic of Binda's classification as a cumulate eucrite.

5.8 THE CLASSIFICATION OF MACIBINI

The achondrite Macibini fell in Zululand, South Africa, in 1936 (HEY, 1966). It was first described by HAUGHTON and PARTRIDGE (1938), who classified it as a eucrite on the basis of comparison of its chemical composition with the compositions of Juvinas, Stannern, Moore County, and Petersburg. However, even in the original comparative data discrepancies are evident; the Macibini analysis contains more Si and considerably less Fe than those of the eucrites to which it was compared by Haughton and Partridge. The more modern analyses used in the present investigation (Table 4.7) do not confirm these differences, but the plotting of inter-element relationships carried out in this chapter have, in many instances, indicated that Macibini is not a typical eucrite. In inter-element plots of refractories in which a differentiation trend for the eucrites can be distinguished that is distinct from the trend calculated for the howardites and diogenites, Macibini tends to plot in a position clear of the eucrite trend and, frequently but not invariably, on the extension of the regression line of the magnesian achondrites (e.g. Figs 5.5, 5.9, and 5.13). In plots in which a single trend

embraces all the achondrites, i.e. chiefly plots involving Mg, Macibini occupies a position intermediate between the 'main group' eucrites and the most Fe-rich howardites, but distinct from the field of the cumulate eucrites (e.g. Figs 5.14, 5.16, and 5.19). In all of the plots that involve element-ratio or ratio-ratio relationships, Macibini is far removed from the eucrite trend. In some of these, e.g. Figs 5.22 and 5.23, it may lie on a straight-line regression calculated for some or all of the more magnesian achondrites (howardites and diogenites), but it does not appear to occupy a position on or near any possible curved mixing lines linking these achondrites with the primary eucrites. Thus, if it is related to the howardites and diogenites, the relationship is more likely to be of an igneous nature - represented by a straight line on ratio plots - rather than mixing, which has been shown by LANGMUIR et al. (1978) to produce curved trend lines.

Macibini is atypical in its texture and mineral chemistry also. REID (1974) described it as "a complex polymict (the underlining is mine) breccia with rock and mineral clasts that are extraordinarily diverse in texture and composition", and noted that the compositional range of its pyroxenes extends continuously from magnesian orthopyroxene to hedenbergite. Such a wide range is characteristic of howardites, and has been recorded in Kapoeta (FREDRIKSSON and KEIL, 1963; DYMEK et al., 1976), Malvern (SIMPSON, 1975), and Yamato 7308 (TAKEDA et al., 1976). In Macibini, the pyroxene compositional trend is even more extensive than in any of the howardites cited; pyroxenes occur with higher contents of Fe and Ca than are normally present even in eucritic pyroxenes (REID, 1974).

Because of these textural and compositional data, SIMPSON and AHRENS (1979) proposed that Macibini should be re-classified as a howardite, and the suggestion retains a certain amount of validity. However, as discussed in section 3.5.3, the discovery of eucrites in the Antarctic that

have polymict textures must be taken into consideration. In the revised nomenclature for the basaltic achondrites proposed by SCORE et al. (1982), magnesian pyroxene that may have originated from diogenites is absent or rare in the polymict eucrites but common in the howardites. Although REID (1974) identified magnesian orthopyroxene in Macibini and observed that "the more magnesian pyroxenes are coarser-grained and tend to occur as mineral clasts", it is not possible at present to quantify these observations. However, plots of inter-element relationships involving Mg (e.g. Figs 5.14 and 5.19) show that Macibini occupies a position on the achondrite trend intermediate between the main group eucrites and the Malvern samples, which have been shown to contain a considerable proportion of magnesian orthopyroxene (Tables 3.2 and 3.3). From this it may be judged that Macibini also contains an appreciable amount of Mg-rich pyroxene. Unfortunately, comparison with polymict eucrites in the Antarctic collections is not yet possible because of the lack of modal and compositional data on them. Until these data become available, the classification of Macibini must remain an open question, as must also the basis for exact distinction between eucrites and howardites.

5.9 TERNARY RELATIONSHIPS IN THE METEORITES STUDIED

5.9.1 Introduction

The inter-element relationships so far examined in this chapter have involved pairs of elements or element ratios. The chapter continues with a study of the ternary relationships between the five most important elements present in the bulk analyses of the 42 meteorites investigated - Si, Al, Fe, Mg, and Ca. This was carried out to establish what trends, if any, occur in the achondrite and mesosiderite data, whether or not these trends are continuous, and the nature of the achondrite-mesosiderite relationship in plots involving three major elements. In addition, the ten

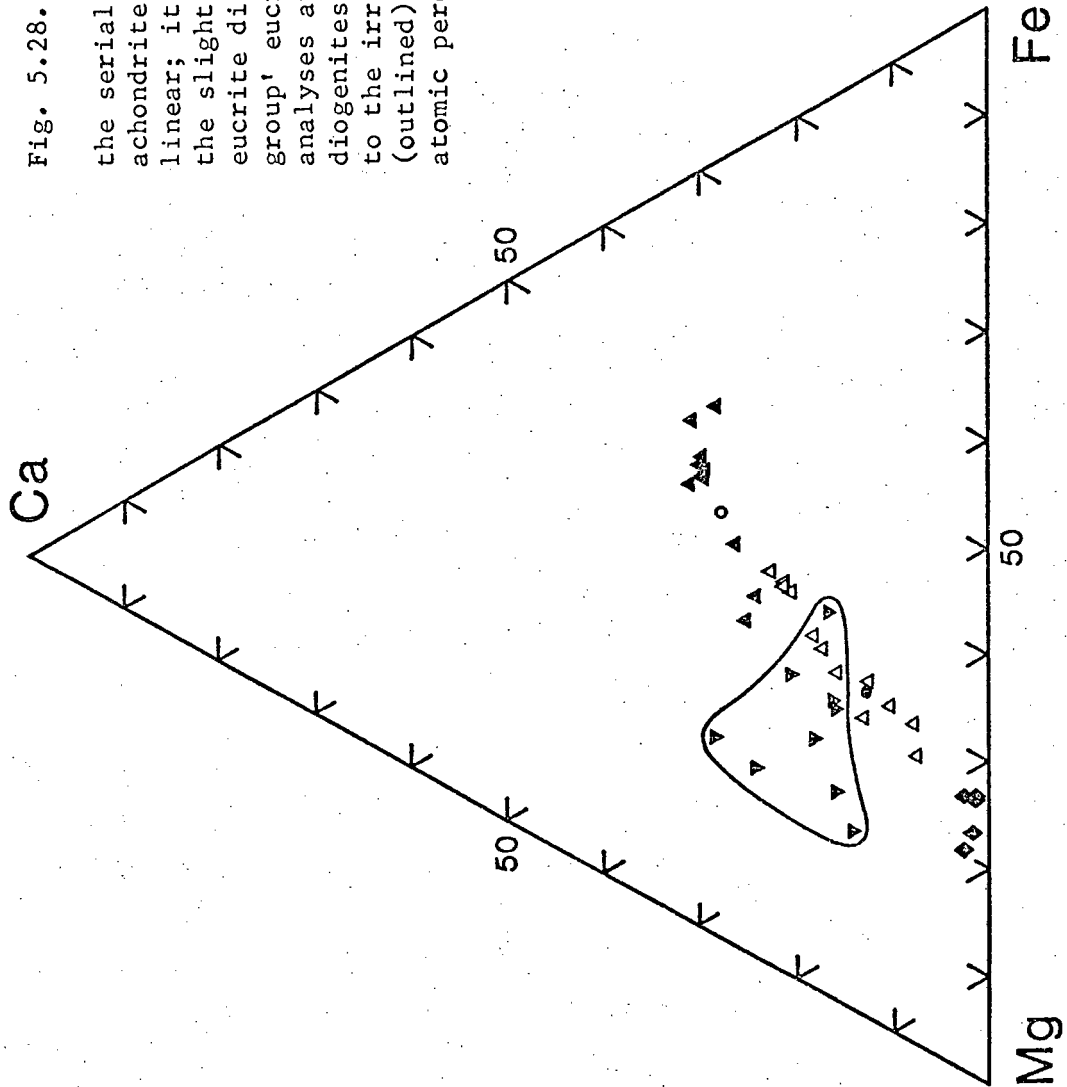
ternary plots resulting from the various possible combinations of the five selected elements provide a basis for comparison with the microprobe data on so-called 'whole-rock' components of Binda, Bununu, Frankfort, Malvern, and Molteno that are similarly plotted in Chap. 7.

5.9.2 The Ca-Mg-Fe relationship

This important relationship is shown in Fig. 5.28. The achondrites define a roughly continuous trend from the Ca-poor diogenites to the Fe-rich eucrites Nuevo Laredo and Lakangaon. The slight curvature of this trend may be apparent only because the eucrites may constitute a subsidiary trend - pivotal about the 'primary' melts - with a higher relative rate of increase in Fe. The plot confirms some of the features noted in the binary relationships studied: the enrichment of Macibini in Mg compared to the 'main group' eucrites and the meteorite's ambivalent position at the possible junction of the two segments of the achondrite trend; the irregular field occupied by the mesosiderites that does not conform to the distribution of the howardites; the large compositional difference between Binda and the cumulate eucrites; and the ambiguous position of the Binda analyses on the achondrite line but in close proximity to the field of the mesosiderites.

The achondrites, whether considered as a whole or as separate (eucrite and howardite-diogenite) series, show continuous chemical variation in this relationship that is strongly suggestive of igneous differentiation. The plot lends some support to the idea of a eucritic differentiation series generated by fractional crystallization of magnesian pigeonite and calcic plagioclase from 'primary' eucritic partial melts (see Chap. 8). Similarly, a range of source materials for the howardites could have been produced by subtraction of Mg-rich orthopyroxenes, comparable to those of the diogenites, from partial melts more magnesian than the liquids parental to the eucrite

Fig. 5.28. The Ca-Mg-Fe relationship in the meteorites investigated, showing the serial variation present in the three achondrite classes. The trend is roughly linear; its apparent curvature results from the slight angular divergence of the separate eucrite differentiation series. The 'main group' eucrites, Macibini, and the two Binda analyses are co-linear with the howardites and diogenites, but Binda plots in close proximity to the irregular field of the mesosiderites (outlined). Compositions are recalculated to atomic percent in this and succeeding plots.



series. No explanation is readily apparent for the irregular distribution of the mesosiderites in this plot.

5.9.3 The Ca-Mg-Al relationship

The plotting of this relationship produces the least complex distribution in the ternary diagrams considered. It is a single, extensive, linear trend stretching from the centroid of the triangle to the Mg vertex (Fig. 5.29c). The only major break in its continuity occurs between the Mg-rich howardites and the diogenites, which plot virtually in the Mg vertex. There is a suggestion that the eucrite series forms a trend that is slightly divergent from the general direction. The 'main group' eucrites, which plot on the main trend, constitute the pivotal point for the divergent sub-trend (cf. Fig. 5.28). Macibini again occupies a position between the 'main group' eucrites and the howardites. The mesosiderites conform to the part of the trend in which the howardites plot, but display a lesser compositional range (within which Binda falls) than the howardites.

The extreme regularity of this relationship again suggests that it is controlled by related igneous processes operating on source materials that are also not randomly related to one another. It is interesting to note, apropos the argument presented in section 5.3.2 on the possibility of derivation of howarditic source materials by progressive oxidation of the metal of the mesosiderites, that the absence of Fe from this relationship appears to allow the mesosiderite silicates to behave in a manner very similar to the howardites. This feature will be seen in other ternary plots considered here that do not involve Fe.

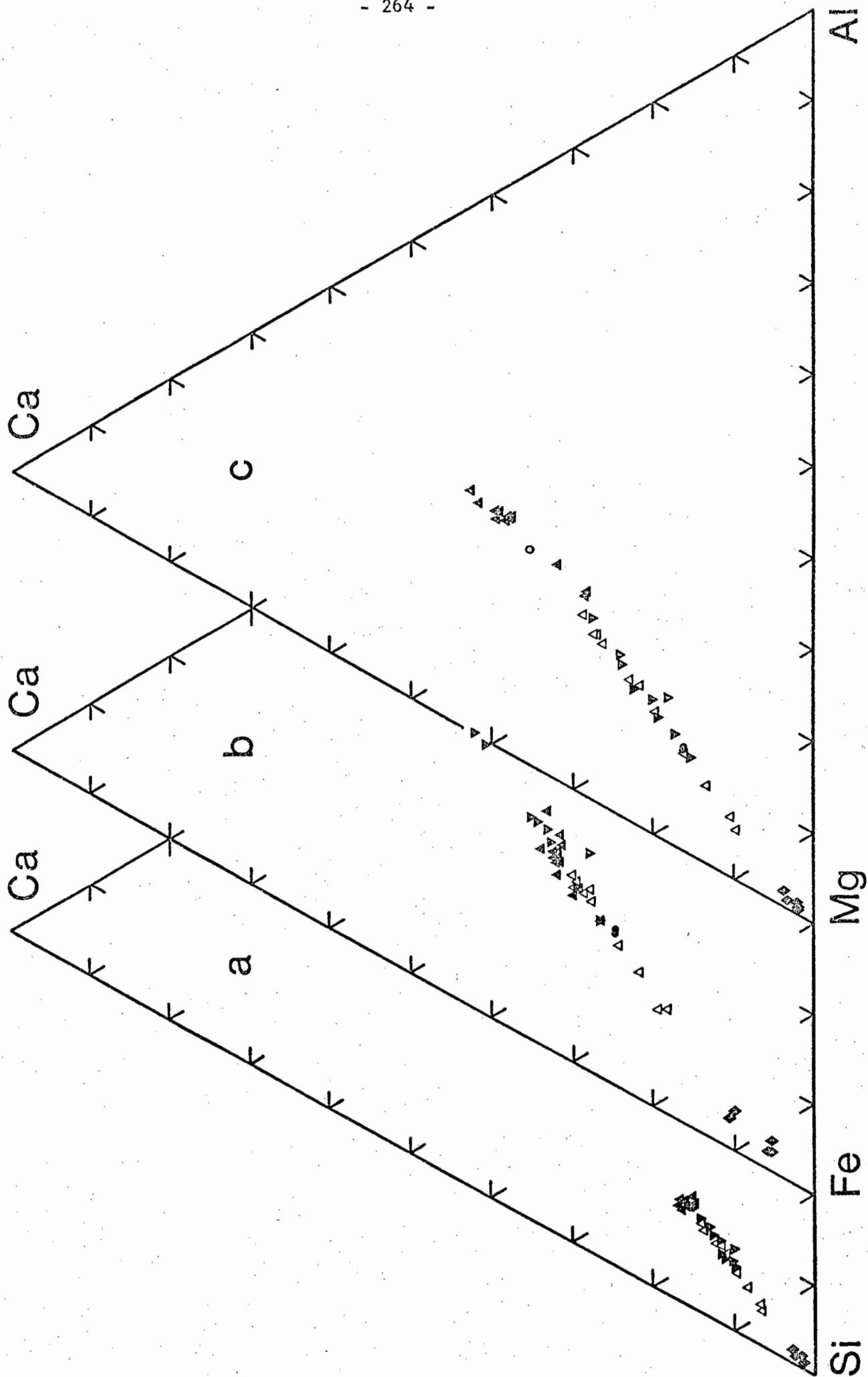
5.9.4 The Ca-Fe-Al relationship

The trend shown by this relationship (Fig. 5.29b) is generally similar to that of the Ca-Mg-Al plot, but is less regular and somewhat discontinuous by comparison. The compositional range of the eucrites and howardites is greatly compressed, with the result that a large gap exists between the howardites and the diogenites which, by contrast, are less compactly distributed than in the previous relationship. The biggest difference is to be seen in the mesosiderites. These plot in an irregular, elongate, discontinuous field stretching from midway in the howardite range to well beyond the most Fe-poor eucrites. The Binda analyses fall at the end of this field nearer to the Fe vertex, on the howardite trend. The overall trend of this relationship is clearly linear, and presumably indicative of the operation of non-random formative processes as discussed above.

5.9.5 The Ca-Si-Al relationship

This is a linear relationship similar to the two previously described but condensed into a small compositional range near the Si vertex (Fig. 5.29a). The distribution of the different meteorite classes is a compressed version of that seen in the Ca-Mg-Al plot (Fig. 5.29c). The eucrite series cannot be distinguished because all members of the class plot in virtually the same place. The mesosiderites coincide with the Si-poor part of the howardite range, and the only noteworthy discontinuity in the trend occurs between the howardites and the diogenites. The regularity of this relationship prompts the same conclusions on the origin of the meteorites involved as are discussed above.

Fig. 5.29. This figure depicts three relationships of similar type: (a) Ca-Si-Al; (b) Ca-Fe-Al; and (c) Ca-Mg-Al. In general, all the meteorites studied plot on a linear trend directed from the centroid of the triangle towards the vertex opposite to the Ca-Al side. In (c), which is the most extensive and continuous trend, the slight angular divergence of the eucrite differentiation series is apparent. Macibini may be slightly displaced from the eucrite trend while plotting on the main trend. A discontinuity of varying size occurs in all three plots between the diogenites and the howardite range. In (a) and (c) - i.e. the relationships not involving Fe - the distribution of the mesosiderites coincides with the part of the howardite range that is richer in Ca and Al. In (b), however, their distribution is less regular and is displaced mainly into and beyond the eucrite field. The two analyses of Binda plot on the main trend, but are closely associated with the mesosiderites in all three ternary diagrams.



5.9.6 The Si-Mg-Al relationship

As with Fig. 5.29, Fig. 5.30 groups together relationships that are generally similar to one another. The Si-Mg-Al relationship is illustrated in Fig. 5.30a. It is approximately linear, with an impression of curvature imparted by the eucrite trend which lies parallel to the Si-Mg side of the diagram. As in other ternaries that do not involve Fe, the mesosiderites coincide with part of the howardite trend, where their presence tends to obscure the near-perfect linearity of that trend. The usual discontinuities are present, that between the howardites and the 'main group' eucrites being partially filled by Macibini. The Binda analyses lie, as usual, on the achondrite trend near the magnesian extremity of the mesosiderite range.

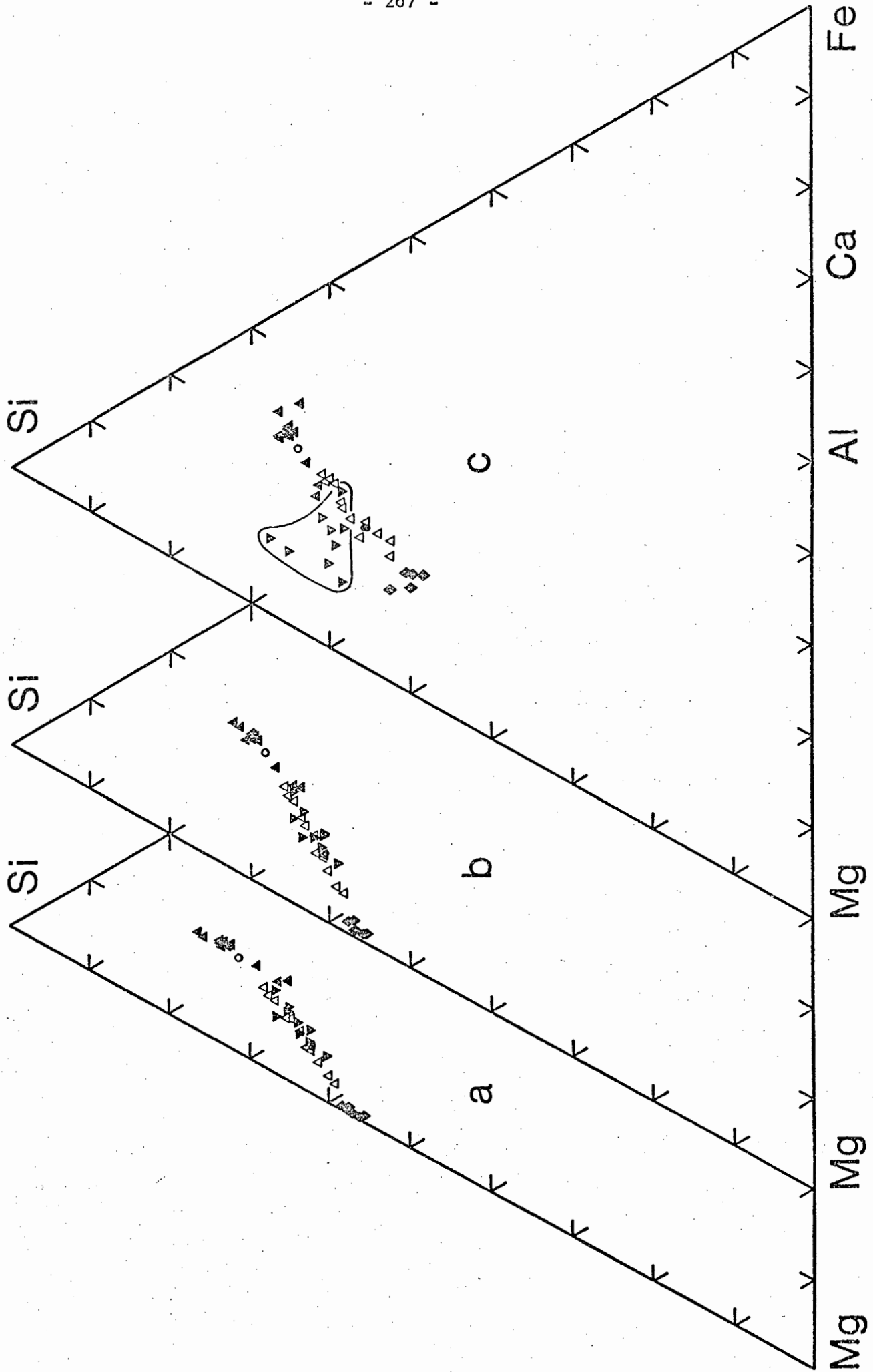
5.9.7 The Si-Mg-Ca relationship

Predictably, this relationship is very similar to that just discussed, with the difference that the eucrite series is less well marked because it does not diverge so sharply from the main trend. The mesosiderites and Binda again plot rather irregularly on and around the well-defined howarditic section of the trend (Fig. 5.30b).

5.9.8 The Si-Mg-Fe relationship

Fig. 5.30c illustrates the effect of the involvement of Fe. The trend of the achondrites is similar in extent and slope to those in the two preceding diagrams, but the mesosiderites plot in an irregular field that transects the howardite compositional range. Other slight differences exist: discontinuities in the achondrite trend are less marked, and the eucrite trend's divergence is in the opposite sense to that of the two previous relationships. Similarities to previous figures include the plotted

Fig. 5.30. The three relationships included in this figure are broadly similar, but that involving Fe (Fig. 5.30c) shows a distribution of the mesosiderites that does not coincide with the achondrite trend (cf. Figs 5.28 and 5.29b). The position of the mesosiderite field indicates that the mesosiderite silicates are richer in Si and Mg than the howardites in the Si-Mg-Fe ternary, but in Figs 5.30a and b, they are virtually identical to part of the howardite compositional range. In all three diagrams, the achondrite trend is approximately linear, as previously noted, with the divergence of the eucrite series most marked in the Si-Mg-Al relationship (Fig. 5.30a). The discontinuity between howardites and diogenites is smaller than in previous figures.



positions of Macibini and Binda relative to the 'main group' eucrites and the mesosiderite field respectively.

5.9.9 The Al-Mg-Fe relationship

This relationship closely resembles that seen in the Ca-Mg-Fe ternary (Fig. 5.28) except that, in this instance (Fig. 5.31a), the eucrite series lies parallel to the Mg-Fe side of the ternary and is therefore easily distinguished from the main achondrite trend that embraces diogenites, howardites, and 'main group' eucrites. The mesosiderites plot in a triangular field similar to those of previously-discussed relationships involving Fe. The howarditic part of the achondrite trend again shows less perfect linearity than when Fe is absent. The Binda analyses are ambiguously associated with the howardites, but in close proximity to the mesosiderite field. Macibini also does not allow of decisive classification in this plot because of its position on both achondrite and eucrite trends.

5.9.10 The Si-Al-Fe relationship

The last two ternary relationships studied have characteristics in common that distinguish them from the others. In this relationship (Fig. 5.31b), the total distribution of the meteorites is seen to be highly condensed. The eucrite series is aligned roughly parallel to the Si-Fe side of the triangle, along which the diogenites are distributed in a range of similar extent. The howardites plot in a narrow belt linking these two trends, while the mesosiderites occupy an elongate field that intersects this belt and is sub-parallel to the eucrites and diogenites. The Binda analyses are in positions common to this field and to the howardite zone.

5.9.11 The Si-Ca-Fe relationship

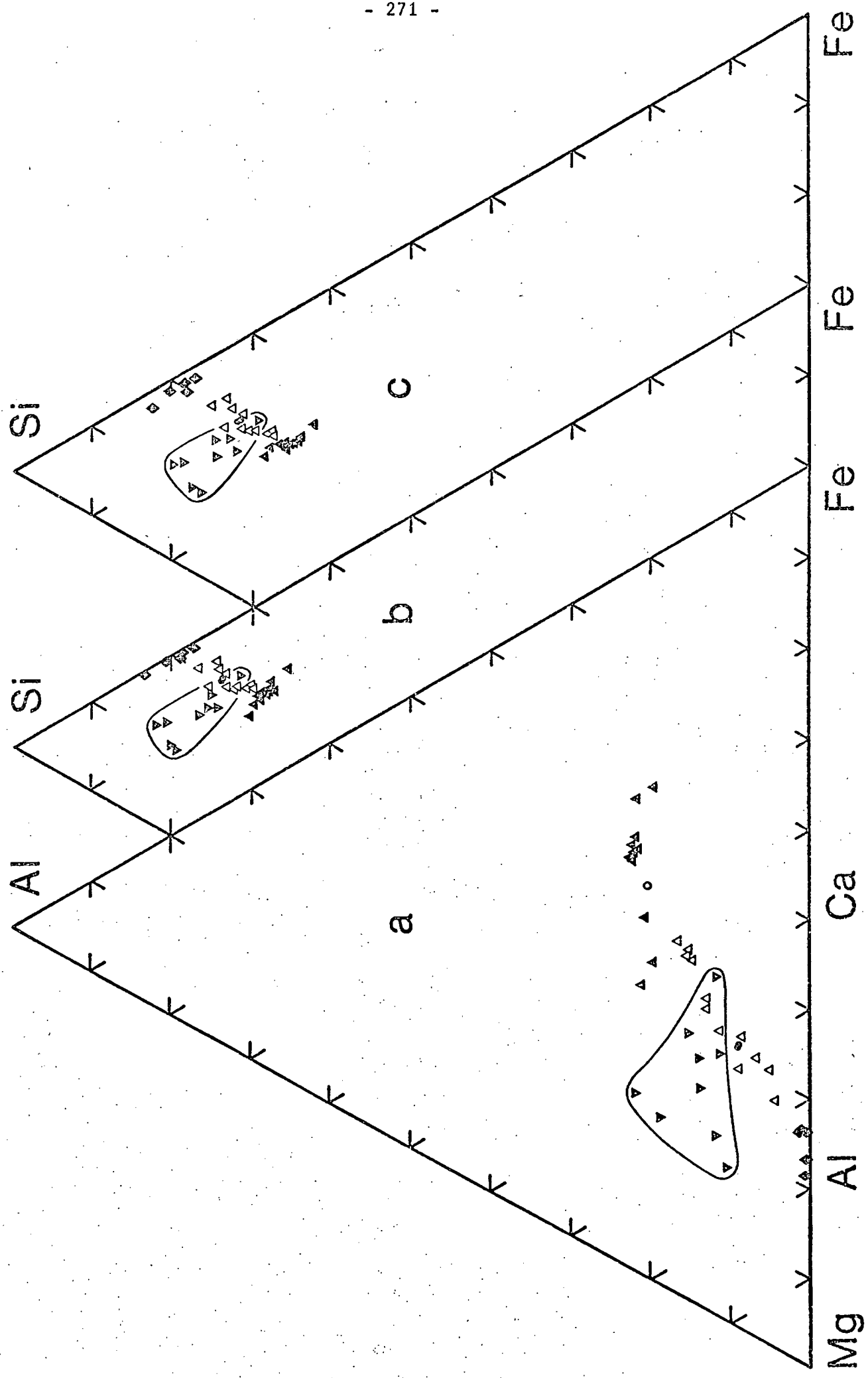
Fig. 5.31c shows this relationship to be almost identical to that just described. The eucrite series is more accurately parallel to the Si-Fe side of the triangle and is slightly farther from the diogenite trend, with the result that the discontinuity between diogenites and howardites is more apparent.

The ten ternary plots considered have shown that, in general, the three main achondrite classes and the silicates of the mesosiderites possess characteristics that clearly distinguish them from one another in terms of the five most important major elements present. In addition, however, these plots have revealed the role played by Fe in the relationship between howardites and mesosideritic silicates; if, for reasons previously discussed, P is allocated to the metal phase, Fe appears to be the only element that distinguishes these two types of meteoritic material. In plots from which Fe is excluded, the mesosiderites are aligned with the howardite trend, which in turn connects the 'centre of gravity' of the diogenite distribution with those eucrites that are thought to represent small amounts of partial melting of the source region (STOLPER, 1977a). In all ten plots, the eucrites can be seen to follow a trend distinct from the serial compositional relationship that pervades the achondrites as a whole, and in some (especially Fig. 5.31) the diogenites define another trend, an observation at variance with their supposed lack of chemical variability.

The chapter concludes with an examination of the information that can be gained by plotting the data used in this investigation in another type of ternary diagram - the 'pseudo-liquidus' diagrams for basaltic achondrite compositions used by STOLPER (1977a, Figs 5, 6, and 8).

Fig. 5.31a. The increased irregularity of the howardite trend and the distribution of the mesosiderite silicates in a roughly triangular field indicate the effect of Fe in this ternary plot. The eucrite 'sub-trend' lies parallel to the Mg-Fe side of the diagram, distinct from the main achondrite trend connecting the diogenites and 'main group' eucrites. The analyses of Binda and Macibini are, as usual, ambiguously situated relative to the main achondrite trend.

Fig. 5.31, b and c. The Si-Al-Fe and Si-Ca-Fe relationships produce almost identical plots in which the distributions are extremely compact and three of the meteorite classes plotted (eucrites, diogenites, and mesosiderites) show trends parallel to the Si-Fe side of the ternary. The howardites occupy irregular zones that join up the diogenites and 'main group' eucrites. The Binda analyses plot within these zones and also within the mesosiderite fields (outlined) in both figures. Macibini is not distinguishable from the eucrites in these two plots.



5.10 'PSEUDO-LIQUIDUS' PROJECTIONS OF THE BULK COMPOSITIONAL DATA

5.10.1 Introduction

In order to represent the results of his experiments graphically, STOLPER (1977a) adapted the projection system used by LONGHI et al. (1974) in a study of Apollo 17 mare basalts to the eucritic compositions with which he was concerned. Pseudo-ternary diagrams could then be constructed from the microprobe analyses of multiply-saturated liquids (WALKER et al., 1972) produced in melting experiments on Juvinas and Sioux County and used to study the relationships of specific phases at their liquid. Stolper projected published compositional data for eucrites on to two such 'pseudo-liquidus' diagrams; the recalculation system used is detailed in the caption to his Figs 5 and 6. This enabled him to demonstrate the clustering of eucrites formed by small degrees of partial melting of the source region around the olivine + pigeonite + plagioclase peritectic of the system. Stolper's study was restricted to those meteorites he considered to be eucrites, so it was decided to extend this method of projection to include all the achondrites and mesosiderites of the present investigation; their molar Fe/Fe+Mg ratios (Table 5.9) are generally sufficiently close to those of the eucrites to permit this. The projections of these data are presented and discussed in the following sections.

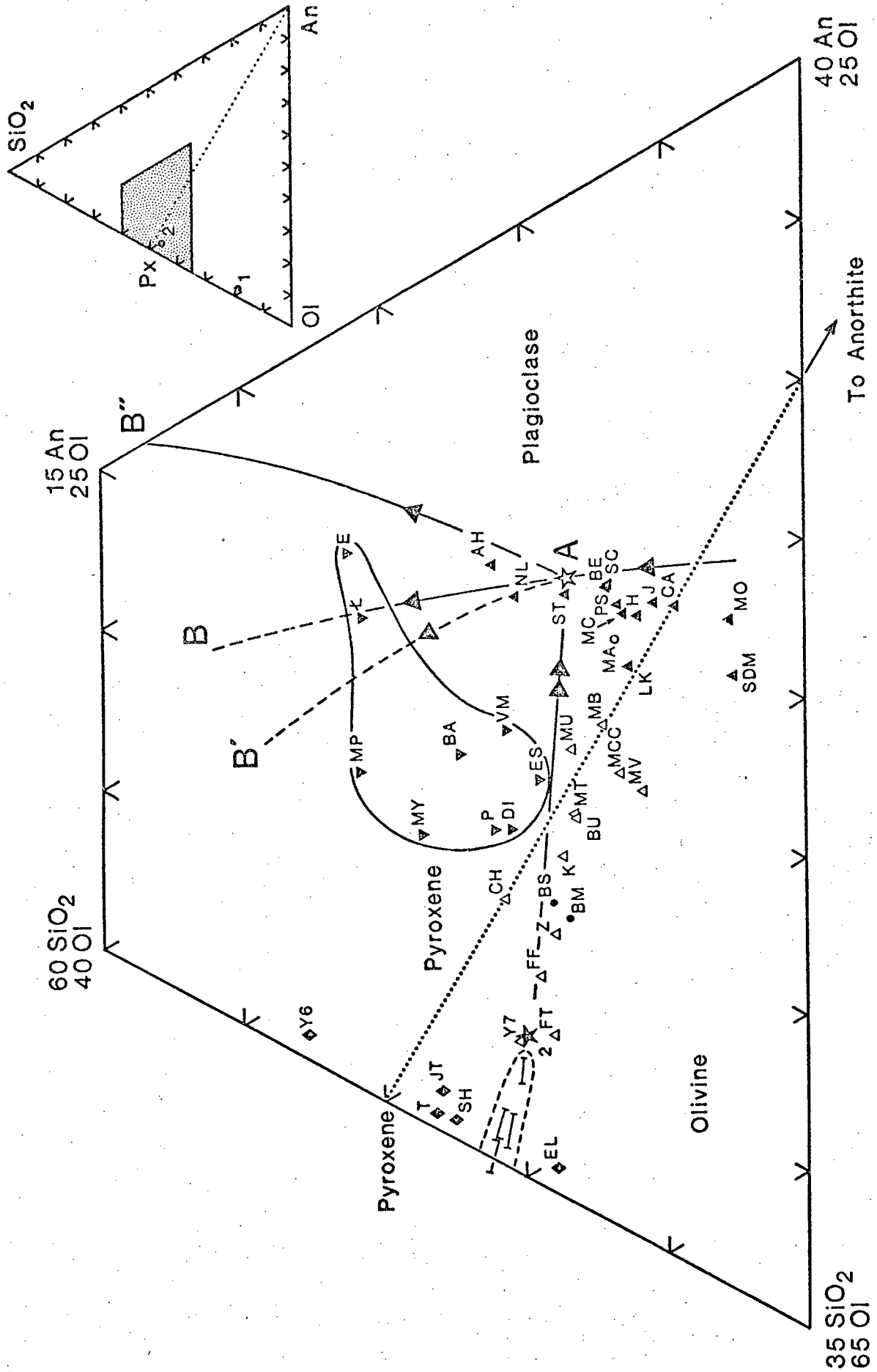
5.10.2 The silica-olivine-anorthite 'pseudo-liquidus' diagram

The projected data on eucrites from the present work (Fig. 5.32) correspond closely with the averages used by Stolper (see his Fig. 5). Small discrepancies in position can be explained by minor differences in the data, particularly since both projections employed are "extremely sensitive" to variations in silica concentration (STOLPER, 1977a, p. 595). The phase boundaries in this projection and in Fig. 5.33 were taken from the

corresponding diagrams in Stolper's paper. The position of the peritectic A in Stolper's diagram is represented by a hollow star in Fig. 5.32, and is only slightly displaced from the location of Sioux County, to which it is adjacent in his figure. The elongation of the eucrite field follows approximately the phase boundary between plagioclase and olivine, leading into that between plagioclase and pyroxene. Nuevo Laredo plots on the plagioclase-pyroxene boundary, which is the path followed by residual liquids produced by fractional crystallization of pigeonite and plagioclase from 'primary' eucritic liquids generated close to the peritectic (path AB' in Stolper's diagram). Lakangaon plots less well in Fig. 5.32 than in the original version. This difference is difficult to explain because, as far as is known, only one analysis of this meteorite has been made (McCARTHY et al., 1974). The cumulate eucrites Moore County, Moama, and Serra de Magé, considered by the present investigator to be the pigeonite-plagioclase accumulations from fractionation of the 'primary' eucritic melts grouped around the peritectic A, tend towards alignment along the plagioclase-olivine boundary, i.e. on the opposite side of A from the residual liquids to which they correspond. Note that the Binda analysis used by Stolper (McCARTHY et al., 1973) and those used in the present work plot in very similar locations, far removed from the eucrites interpreted as cumulates by Stolper.

The howardite analyses used in the present study project in a roughly linear pattern lying along the boundary between the fields of olivine and pyroxene in Stolper's Fig. 5. This irregular line, which incorporates the Binda analyses and Macibini, connects the 'primary' eucrites with a point in the diogenite field between Ellemeet and a group made up of Johnstown, Shalka, and Tatahouine. The remaining diogenite, Yamato 6902, plots at some distance from the others both in this and the succeeding diagram because of its higher content of SiO_2 (Table 4.10).

Fig. 5.32. The silica-olivine-anorthite 'pseudo-liquidus' projection (based on Fig. 5 of STOLPER, 1977a) in which the analyses of the 42 meteorites discussed in this chapter have been plotted. The inset shows the position of the enlarged portion depicted in this figure, and also the projected locations of Stolper's Source Regions 1 and 2. Source Region 2 is represented in the main figure by a solid star, the peritectic A (as plotted in Stolper's Fig. 5) by a hollow star. As in the original, the eucrites that are thought to be 'primary' partial melts from the source region cluster around A, while the derived eucrites are aligned along the olivine-plagioclase and pyroxene-plagioclase boundaries. The more magnesian achondrites plot on the olivine-pyroxene reaction curve. Source Region 2 also lies on this boundary, as does the compositional field (demarcated by a dashed line) of the residues produced by the partial melting of the source material that generated the eucrites Juvinas, Sioux County, Haraiya, and Stannern. The mesosiderite silicates (outlined field) do not coincide with either group of achondrites, but occupy more silica-normative positions within the pyroxene liquidus field. The Binda analyses lie on the boundary, among the howardites, but close to the highest concentration of mesosiderites.



As in many previous plots, the mesosiderites occupy an irregular field adjacent to the howardites. All are richer in the SiO_2 component than the howardites that define the trend described above. Four of the so-called 'primary' mesosiderites (this work) - Emery, Łowicz, Mount Padbury, and Mincy - show the greatest enrichment in this component. Patwar and Vaca Muerta, for which intermediate oxidation is proposed, have lower degrees of SiO_2 enrichment. NEHRU et al. (1978) reported the occurrence of tridymite in Emery and "other mesosiderites", and postulated the presence of a component greatly enriched in tridymite and phosphate in these meteorites. MALISSA (1974) found tridymite in all four mesosiderites he studied; these included Estherville, Mincy, and Vaca Muerta. Unfortunately, quantitative modal data are lacking, but it is possible that the 'primary' mesosiderites contain more of the tridymite-phosphate material than the more oxidized types (Fig. 5.32). There is, however, no real correlation between the concentrations of SiO_2 and P_2O_5 in the mesosiderite analyses (Table 4.4).

From Fig. 5.32 and Stolper's Fig. 5, therefore, it may be concluded that eucrites and howardites project in positions that lie on phase boundaries of the pseudo-ternary system, with the 'primary' eucrites concentrated around its peritectic. By contrast, the mesosiderite silicates plot entirely within the pyroxene field. Two examples (Emery and Łowicz) may, however, fall on or near the point at which silica would crystallize from a liquid (between B and B' in Stolper's Fig. 5, depending on the course of crystallization followed from the peritectic A). These meteorites do not have the high $\text{Fe}/\text{Fe}+\text{Mg}$ ratio (Table 5.9) associated with such a position in the system, and it is possible that their projected locations cannot be relied on in relation to phase boundaries postulated for liquids of higher $\text{Fe}/\text{Fe}+\text{Mg}$ ratios. In addition, this particular diagram is not sensitive to variation in Fe and Mg; the second 'pseudo-liquidus' diagram (Fig. 5.33) conveys a more accurate

impression of the relationship between the Fe- and Si-rich liquids residual from the crystallization of the eucrites and the more siliceous members of the mesosiderites.

In several of the relationships previously examined in this chapter, the possible source region compositions proposed by STOLPER (1977a) were plotted and inferences were drawn from these plots on which of the two compositions appears to be the more useful in trying to arrive at an understanding of the genesis of the achondrites; see Figs 5.20, 5.22, and 5.23 and the discussion in sections 5.5.1, 5.5.3, and 5.6.1. In the inset to Fig. 5.32, the approximate locations of Source Regions 1 and 2 are shown. As in the figures cited above, Source Region 2 appears to be the more relevant to the formational processes that have taken place in the achondrites because it projects within the part of the pseudo-ternary that is occupied by the entire compositional range of these meteorites and, moreover, of the possibly related mesosiderite silicates. The following discussion accordingly centres on this composition.

Using the approach adopted in the figures cited above, the compositional ranges of residues produced by the percentages of partial melting of Source Region 2 required to generate liquids similar to the compositions of four key eucrites were plotted in Fig. 5.32. These ranges define an elongate area stretching from Source Region 2 to the edge of the diagram as an extension of the howardite trend described above. The residual compositions therefore lie on, or very close to, the boundary between the fields of pyroxene and olivine. The theoretical requirement that the composition of the residue should reach the edge of the diagram simultaneously with exhaustion of plagioclase from the source materials appears to be satisfied. STOLPER (1977a) reasoned, from the flat rare earth element pattern of Juvinas, that plagioclase was exhausted at about the degree of partial

melting (15-20%) required to generate liquids compositionally similar to Juvinas and Sioux County. This is confirmed in Fig. 5.32; the plotted ranges of the residues from the formation of these eucrites virtually reach the boundary of the 'pseudo-liquidus' diagram. That for Haraiya extends beyond the edge, indicating that the upper limit of melting (25%) calculated for this eucrite (section 5.5.1) is slightly too high. The final residues would consist essentially of pyroxenes with Fe/Fe+Mg ratios similar to those of the diogenites similarly situated in the projection, viz. 0.24 (MASON and JAROSEWICH, 1971; FREDRIKSSON et al., 1976). This value is identical to that implicit in the data of WEIGAND (1975) for the pyroxenes in the source regions of the mesosiderite Patwar at the stage at which plagioclase was exhausted; this was noted, but not accepted, by STOLPER (1977a, p. 606). Lesser degrees of partial melting would result in residues with higher Fe/Fe+Mg ratios, i.e. closer to that of the source region (0.334; Table 5.8). The implications of these and other observations are further discussed in Chap. 9, in which a model for the formation of the achondrites is presented.

Also noteworthy in Fig. 5.32 and the succeeding projection is the proximity of the howardite Yamato 7308 to the plotted position of Source Region 2; the degree of similarity can be gauged from Table 5.12. The importance of this observation lies in Yamato 7308 having been selected, on the basis of its Yb/Sc ratio (used as an index of planetary fractionation), as the least fractionated sample from the eucrite parent body by PALME et al. (1978). These authors state (p. 38): "Although Yamato 7308 itself may have had a more complex origin, a chemical composition similar to Yamato 7308 must have played a fundamental role in the evolution of the eucrite parent body. The starting material from which both eucrites and diogenites were fractionated might have had this composition." They draw attention also to the near-identity of the PR* composition (DREIBUS et al., 1977) and that of

Table 5.12. A comparison of the howardite Yamato 7308 with two estimates of the composition of the source material from which the achondrites may have been derived

	Source region 2	Yamato 7308	PR*
Source	1	2	3
SiO ₂	50.24	52.14	51.17
TiO ₂	0.22	0.22	0.23
Al ₂ O ₃	3.65	3.72	4.57
Cr ₂ O ₃	2.74	0.69	0.99
FeO*	18.56	16.34	16.81
MnO	0.67	0.58	0.52
MgO	20.77	22.49	20.93
CaO	3.10	3.57	3.96
Na ₂ O	0.05	0.16	0.14
K ₂ O	--	0.06	--
TOTAL	100.00	99.97	99.32
Ca/Al(wt)	1.147	1.296	1.169
Fe/Fe+Mg (molar)	0.334	0.290	0.311

Sources of data: 1 Table 5.8, this work
 2 Table 4.10, this work
 3 Table 1, Dreibus et al. (1977)

Yamato 7308. Dreibus and his colleagues derived this composition, which is that of the primary material of the eucrite parent body, by selecting from the mixing diagrams they used to study the formation of the howardites the composition whose Al/Sc ratio corresponds with that of C1 chondrites (1370). The PR* composition, recalculated from Table 1 of the Dreibus paper, is compared to those of Source Region 2 and Yamato 7308 in Table 5.12. The correspondence between the three is reasonably close for most oxides. Thus three completely different approaches converge on broadly similar estimates of composition for the source material from which the major types of achondrite may have been derived.

DREIBUS et al. (1977) reasoned further that addition of 47% olivine with the composition of that in the lunar dunite 72417 to PR*, the primary source material for the achondrites, would produce a bulk composition for the eucrite parent body with the Mg/Si ratio of C1 chondrites (0.91). This interesting observation may be returned to when a model for the formation of the main classes of achondrites is considered.

The pseudo-ternary projection shown in Fig. 5.32 was used by MITTLEFEHLDT et al. (1979) in a somewhat different way from the present investigation, although they selected the data from this laboratory (including my new data on howardites and mesosiderites presented in SIMPSON and AHRENS, 1977) as being the most precise and therefore best suited to illustrating their arguments. The general distribution of the main achondrite classes and the mesosiderite silicates is, of course, very similar to that of Fig. 5.32, but the diagram was used in support of their belief that mesosiderites were formed by the addition of a eucrite-like component with high normative silica to howarditic material. Their Fig. 4 outlines two methods by which such a component might have been produced. Liquids with compositions lying between B and B' in Fig. 5 of STOLPER (1977a), i.e. residual liquids

resulting from crystallization of pyroxene and plagioclase from primary eucrites at or near the peritectic A, were rejected because none of the material in mesosiderites shows the REE patterns that would be present in such liquids. Instead, these authors proposed fractionation of pyroxene from an arbitrarily selected diogenite parent liquid, supposedly situated on the olivine-pyroxene reaction boundary, as a means of driving residual liquid compositions towards the ternary eutectic B; in the same process, diogenite-like cumulates would be produced.

The present investigation does not support this hypothetical model for the formation of the mesosiderites. None of the many inter-element relationships examined in this chapter provide any positive evidence in favour of such a model. In only one of the direct relationships are the distributions of howardites and mesosiderites practically coincident and, at the same time, distinct from that of the eucrites (the Ca-Al relationship: Fig. 5.1). In many other inter-element plots (e.g. Figs 5.2, 5.3, 5.9, and 5.12), the mesosiderites occupy a position intermediate between the magnesian end of the howardite trend and the cumulate eucrites, but never in distributions that suggest mixing of any howarditic composition with these cumulates or with a Si-enriched, eucrite-like basaltic component. Neither do the relative positions of the mesosiderites and the proposed eucritic and howarditic end-members in Mittlefehldt's Fig. 4 compellingly indicate any such mixing relationship.

More critical to the argument, however, is the position of the olivine-pyroxene reaction curve and therefore the composition (or compositional field) that, according to the model, gave rise to diogenitic cumulates and siliceous residual liquids. In Fig. 5.32, the howardites included in this study project along a line connecting the peritectic A (STOLPER, 1977a) with the diogenite field; it is no coincidence that this is the position of

the olivine-pyroxene boundary in Stolper's Fig. 5. Stolper's Source Region 2 also plots on this line, exactly where it should according to theoretical reasoning (STOLPER, 1977a, p. 600), which indicates that after plagioclase had been exhausted in the source material by the partial melting that produced the primary eucrites with compositions close to the peritectic A, further partial melting would result in melts whose compositions changed progressively along the olivine-pyroxene reaction boundary to the point at which pyroxene was exhausted in the source. This point was dependent on the amount of previously-generated plagioclase-bearing melt remaining in the source area, but probably lay in the field of the residues, between the edge of the diagram and the position of Source Region 2 which, by definition (see Table 5.8), contained only negligible olivine. Fusion would therefore have reached completion at that point, without significant production of melts from which olivine would have crystallized. As shown previously, 'diogenitic' residues with compositions ranging from close to that of Source Region 2 to pure orthopyroxenite would have been produced by the partial fusion that generated the primary eucrites. The minor olivine present in certain diogenites (HEWINS, 1981) is presumably residual from this partial fusion. The division of diogenites into olivine-bearing and olivine-free varieties in Mittlefehldt's Fig. 2 is not supported by the work of HEWINS (1981) or FLORAN et al. (1981).

In Fig. 5.32, therefore, there is a clear correspondence between the observational (plotted) data and theoretical reasoning based on the Stolper model. Moreover, it appears logically sounder to base genetic arguments on a source composition derived from experimental petrology than on one that is arbitrarily chosen. The Mittlefehldt model relies, for its validity, on the relative positioning of the arbitrary source composition, the olivine-pyroxene boundary on which it was placed, and the composition of the pyroxene

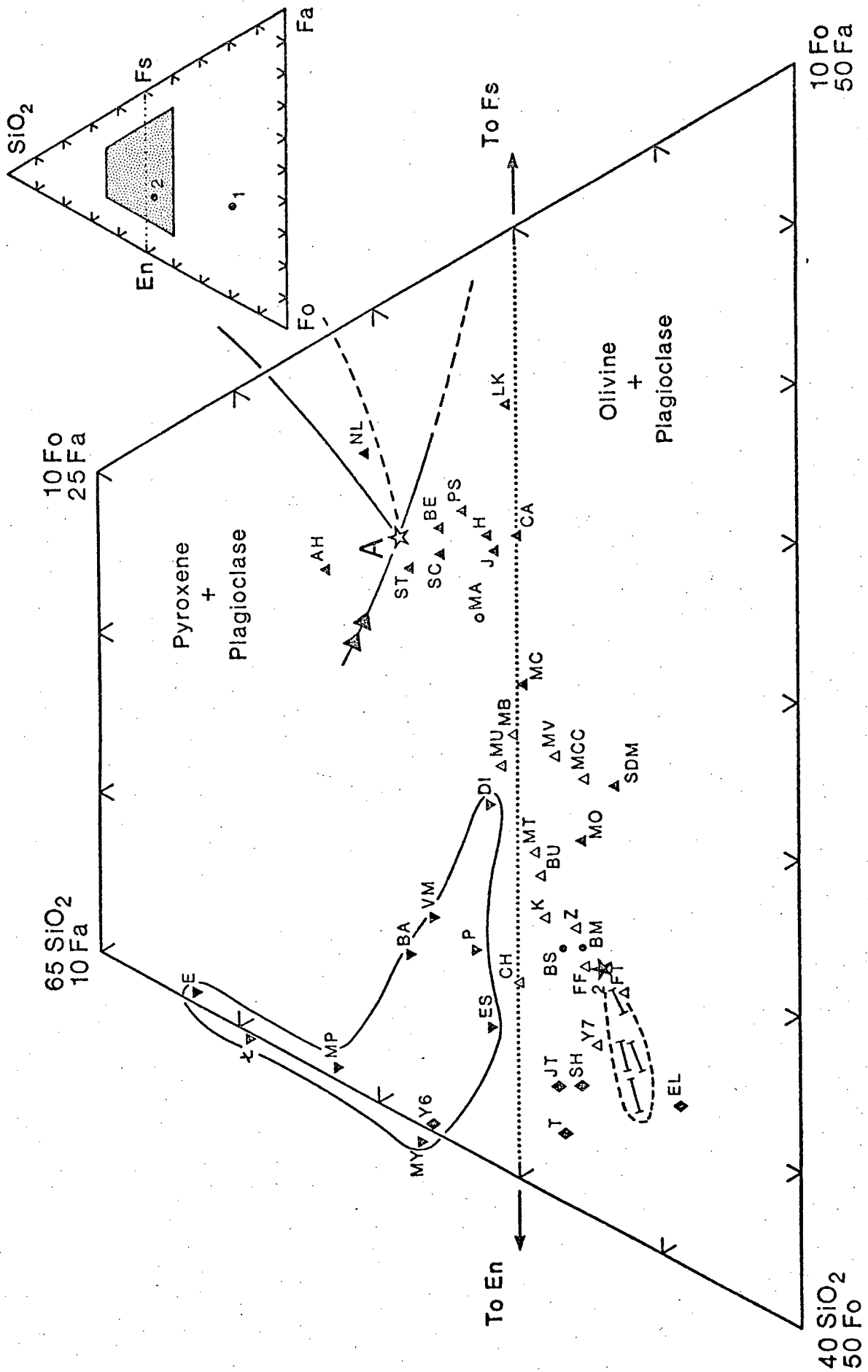
that was supposedly fractionated to produce the necessary Si-enriched residual component (MITTLEFEHLDT et al., 1979, Fig. 4b). The olivine-pyroxene boundary chosen by Mittlefehldt and his associates was taken from Fig. 8 of STOLPER (1977a) in which the results of melting experiments on Binda are diagrammatically represented. This boundary occurs in a position different from that shown in Stolper's Fig. 5, in which his compositional data are projected, and different from that suggested by the trend of the howardites and diogenites included in the present investigation. It is possible that Binda was an unfortunate choice for this purpose because of the uncertainty surrounding its true classification.

5.10.3 The silica-forsterite-fayalite 'pseudo-liquidus' diagram

The analyses used in the present study were plotted also in this, the second of the 'pseudo-liquidus' projections used by Stolper (his Fig. 6). The diagram (Fig. 5.33) is complementary to that discussed above and shows the liquidus fields of olivine, pyroxene, and silica in the plane of plagioclase saturation. Its chief usefulness lies in the fact that, unlike the previous diagram, it is sensitive to Fe-Mg variations. This feature causes the achondrites to be aligned in the projection according to their relative contents of these elements, but the mesosiderites are clearly distinguished by reason of their greater richness in Mg and Si (Fig. 5.33). The 'primary' eucrites cluster, as previously, around the peritectic A. The residual liquid Nuevo Laredo occurs at the end of the achondrite trend as expected but, as in Fig. 5.32, Lakangaon does not plot well.

As in the previous diagram, Stolper's Source Region 2 was used to obtain the compositional ranges of the residues produced by the partial melting of that source required to produce the eucrites Juvinas, Sioux County, Haraiya, and Stannern. The compositional field thus defined extends

Fig. 5.33. The silica-forsterite-fayalite 'pseudo-liquidus' diagram used by STOLPER (1977a, Fig. 6) to show the relative positions of the members of the eucrites on the plane of plagioclase saturation. The symbols used are the same as for Fig. 5.32. The achondrites included in the present study form a poorly-defined trend stretching across part of the olivine + plagioclase field and extending into that of pyroxene + plagioclase, with the 'primary' eucrites concentrated in the vicinity of the peritectic A (see Stolper's Fig. 6). Residues from the partial melting of Source Region 2 extend into the diogenite field, as in the previous figure. The mesosiderites show an irregular distribution (outlined) distinct from that of the achondrites.



along the achondrite trend to link up with the diogenite field but does not project beyond it. These observations are in accordance with those made from the previous diagram and fully discussed in the preceding section but, because Fe-Mg variation can be better illustrated in this pseudo-ternary projection, some additional light can be thrown on the Mittlefehldt model for the formation of mesosiderites by the mixing of howarditic and Si-rich eucritic components. Unlike in the silica-olivine-anorthite diagram, pyroxenes of definite composition can be plotted in Fig. 5.33. It can therefore be shown that fractionation of pure enstatite from a melt of composition similar to Source Region 2 would not produce residual liquids that would move progressively closer to the ternary eutectic, with consequent enrichment in Si, as postulated by the model. Moreover, if the fractionating orthopyroxene were to contain some Fe, as in the diogenites, the divergence would be increased. This observation reinforces the objections to the model set out in the preceding section.

This chapter has set out the observations and conclusions, some of which are of a tentative nature because of lack of critical data, that have resulted from a study of the inter-element relationships in the bulk chemical data on the 42 meteorites included in the investigation. Some of these observations and conclusions will be discussed, in conjunction with data from other parts of the investigation, in the final chapter of this report. There an attempt will be made to integrate all the lines of evidence into a model which, it is hoped, will clarify some aspects of the formation of the achondrites and their relation to the silicate portions of the mesosiderites.

CHAPTER 6

CHEMICAL COMPOSITIONS OF MINERAL AND LITHIC COMPONENTS OF FIVE BRECCIATED ACHONDRITES

If a little knowledge is dangerous,
where is the man who has so much as
to be out of danger?

Thomas Huxley (1825-1895)

6.1 INTRODUCTION

The investigation reported produced a considerable number of electron microprobe analyses of the clastic constituents of five achondritic (or non-chondritic) breccias - Binda, Bununu, Frankfort, Malvern, and Molteno (Table 1.2). As explained in Appendix 3 and Chapter 1 (section 1.4), many multiple analyses of clasts were carried out and were averaged to obtain better compositional data. Only the data set containing these averages was used in the computational and graphical procedures that accompanied interpretation of the analytical information, but the original data are included in this report as Appendix 2.

The quantity of analytical data obtained necessitated presentation on microfiche cards (Appendices 1-5). These cards contain also a directory of sample names and CIPW norms of all glassy clasts analyzed, as detailed in Chapter 1 and Appendices 1 and 5 respectively. However, because continual reference to microfiche records is both inconvenient and impractical, analyses selected as representative of the various phases analyzed in the five meteorites are tabulated in this chapter. These make up about 10% of the total averaged data. Abbreviated norms of all analyses representative

of glassy phases are also tabulated here. Finally, tables of the oxide or element concentration ranges present in each type of mineral and lithic component analyzed, and the ranges in the normative mineralogy derived from analyzed glassy materials, are included. These ranges are, of course, taken from the full (microfiche) data sets in Appendices 3 and 5 respectively.

The arrangement of the data tabulated in this chapter and in the Appendices is as follows: (1) A division into crystalline and glassy materials is made, the crystalline phases being treated first. (2) The crystalline materials, both opaque and non-opaque, are tabulated in alphabetical order. (3) The glassy materials are presented in the sequence glasses - glassy microbreccias - devitrified glasses. (4) The analyses within each of the mineral or lithic subdivisions are arranged under the headings of the appropriate meteorites, which are listed in alphabetical sequence.

6.2 - CHEMICAL COMPOSITIONS OF THE NON-OPAQUE MINERALS

Analyses of non-opaque minerals, particularly pyroxenes and plagioclases, make up the bulk of the data on all five achondrites. The information given in the following sections is intended to facilitate reference to the tabulated data on the various minerals. Throughout the data presentation, no subdivision has been made on the basis of mode of occurrence of the analyzed phases, but information on occurrence is generally available in full in the directory of sample names (Appendix 1). Such information appears also in a 'sample directory' on each page of computer-generated tabulation of analyses (Appendices 2 and 3), but in a truncated form. This truncation, together with the fact that the averaged analyses of Appendix 3 are designated only by sample number and the description 'AVERAGE (X)' where X is the number of analyses included in the average, necessitated the compilation

of Appendix 1. The computer listings of Appendices 2 and 3 contain also recalculations of the analyses, where appropriate, to atomic proportions on the basis of a specified number of oxygens, and recalculations in terms of the parameters normally used in the binary or ternary plotting of the minerals concerned.

6.2.1 Pyroxenes

Representative analyses of the pyroxenes present in the five achondrites are set out in Table 6.6. The complete original data appear in Tables A2.22 - A2.27, the averaged data in Tables A3.22 - A3.27. During the investigation of Malvern, the first meteorite to be studied using the electron microprobe, ortho- and clinopyroxenes were considered separately, but this approach was discontinued for the other meteorites. The concentration ranges present in the five achondrites studied are set out in Table 6.17.

6.2.2 Plagioclases

Typical plagioclase compositions observed in the various meteorites are presented in this chapter as Table 6.5, and the full original and averaged data sets in microfiche form as Tables A2.16 - A2.21 and Tables A3.16 - A3.21 respectively. In the early stages of the investigation, 42 partial analyses of plagioclases in Malvern were obtained. These analyses have not been used as fully as the complete versions, but are included in the appendices as Tables A2.20 and A3.20. The observed concentration ranges in the plagioclases are set out in Table 6.16.

6.2.3 Olivines

As noted in Chapter 3, olivines were found only in Malvern and Molteno, and are very sparse even where they do occur. Representative

analyses are tabulated in Table 6.4, with supporting data in the appendices as Tables A2.14 and A2.15, and A3.14 and A3.15. Oxide concentration ranges for this mineral may be found in Table 6.15.

6.2.4 Silica minerals

These are very rare in the achondrites studied, and are not represented in the text tables. Data on these minerals appear in Tables A2.28 - A2.30 and in the correspondingly numbered tables in Appendix 3.

6.3 CHEMICAL COMPOSITIONS OF THE OPAQUE MINERALS

The mode of presentation of the analyses of opaque minerals is similar to that of the non-opaques, but attention is drawn to the fact that some of the computer calculation of plotting parameters for chromites and ilmenites is not meaningful because of the absence of Fe_2O_3 from the analyses (see Appendix 2 for a discussion of this problem).

6.3.1 Chromites

Representative analyses of chromites from all five achondrites are given here in Table 6.1. The original data appear in Tables A2.1 - A2.5, and the derived averages in Tables A3.1 - A3.5. The oxide ranges present in the mineral in the various meteorites are set out in Table 6.12.

6.3.2 Ilmenites

No ilmenites were analyzed in the howardite Frankfort. Typical data from the other achondrites are presented in Table 6.2. The complete sets of analyses and averaged analyses are appended to this report as Tables A2.6 - A2.9 and Tables A3.6 - A3.9 respectively. The ranges in these data are given in Table 6.13.

6.3.3 Troilites

Troilites were analyzed only in Malvern and Molteno, and are represented in this chapter in Table 6.7. The Molteno troilites were analyzed only for Fe and S. No recalculations were carried out by computer, but the Fe:S ratio was calculated for the representative analyses in the text. The full original analyses and the averages derived from them are set out in Tables A2.31 and A2.32, and Tables A3.31 and A3.32.

6.3.4 Metals

The metal phase occurs in all five achondrites (although only one tiny grain was found in Binda), but was not analyzed in Frankfort. Representative analyses of the metals are presented in Table 6.3, and the compositional ranges encountered in the metal phase are tabulated in Table 6.14. Appendix 2 contains the original analytical data in Tables A2.10 - A2.13, while the averaged data may be found in the corresponding tables in Appendix 3.

6.4 CHEMICAL COMPOSITIONS OF THE GLASSY PHASES

The glassy phases in the five meteorites comprise the so-called 'true' glasses, devitrified glasses, and the matrix material of the glassy microbreccias. They were regarded as 'whole rock' clasts, and were analyzed for all ten elements normally determined by electron probe microanalysis (see Appendix 8). In addition, the S contents of several abnormal glassy clasts in Molteno were determined. The computer recalculations appropriate to mineral analyses were not, of course, carried out for these 'whole rock' analyses.

6.4.1 Glasses

As noted in Chapter 3, 'true' glasses were found in only Bununu, Malvern, and Molteno. Analyses representative of these glasses are set out in Table 6.8. The original data are appended in Tables A2.33 - A2.35, and the averaged data in Tables A3.33 - A3.35. The oxide concentration ranges present in the averaged data are given in Table 6.19.

6.4.2 Glassy microbreccias

Glassy microbreccias occur in all five achondrites, but in widely varying amounts; Frankfort contains only a single clast in the sample examined. Table 6.9 presents analyses typical of the matrix materials of these microbreccias. Supporting data are to be found in the appendices (Tables A2.36 - A2.40 and Tables A3.36 - A3.40), and the compositional ranges present in the averaged set of data are set out in this chapter (Table 6.20).

6.4.3 Devitrified glasses

The devitrified glassy materials in Malvern were treated as a separate phase, but this was not attempted for the other meteorites because of the difficulty of distinguishing these materials from glassy microbreccias, many of which exhibit some devitrification of their matrices. The analyses selected to represent the Malvern devitrified glasses are therefore listed along with the glassy microbreccias (Table 6.9), and data on their compositional variability are incorporated in Table 6.20. Full data on these devitrified materials are presented in the appendices (Tables A2.41 and A3.41).

6.5 NORMATIVE COMPOSITIONS OF THE GLASSY PHASES

Normative data on the glassy and devitrified materials that occur in the five achondrites are listed in full in Appendix 5, but abbreviated norms calculated from the representative analyses of Tables 6.8 and 6.9 are included in this chapter for ease of reference. They take the same form as the norms of the bulk meteorites (Tables 4.12 - 4.16), with which they are compared in Figs 6.1 - 6.6.

6.5.1 Glasses

Norms of representative analyses of glasses in Bununu, Malvern, and Molteno (Table 6.8) are presented in Table 6.10. The complete set of norms calculated from the averaged data in Appendix 3 (Tables A3.33 - A3.35) may be found in Tables A5.1 - A5.3. The ranges, in cation %, observed in the main normative minerals of the glasses of Bununu, Malvern, and Molteno are also tabulated in this chapter (Table 6.21).

6.5.2 Glassy microbreccias

Table 6.11 contains norms of the typical analyses of glassy microbreccias that appear in Table 6.9, and the complete body of normative data on these phases is recorded on microfiche in Tables A5.4 - A5.8. The variability in the normative mineralogy of these microbreccias is summarized in Table 6.22.

6.5.3 Devitrified glasses

Norms of the devitrified glasses in Malvern, and the ranges exhibited by the main normative minerals in the complete data set of norms (Table A5.9), are presented in the same tables as the glassy microbreccias (Tables 6.9 and 6.22).

Table 6.1. Analyses representative of the chromites present in the five achondrites studied

Meteorite	B I N D A			B U N U N U				F R A N K F O R T	
	B I C R 01	B I C R 29	B I C R 33	B U C R 05	B U C R 10	B U C R 14	F R C R 07	F R C R 11	
TiO ₂	1.62	2.18	2.02	2.06	0.60	1.19	0.73	1.70	
Al ₂ O ₃	9.57	9.38	10.48	9.00	8.00	16.31	7.53	10.62	
Cr ₂ O ₃	53.68	53.20	52.63	53.43	58.04	49.45	57.99	53.47	
FeO*	32.00	31.41	32.16	32.10	29.62	27.50	31.46	32.92	
MnO	0.36	0.34	0.34	0.34	0.37	0.33	0.36	0.35	
MgO	1.87	2.69	2.19	2.37	3.08	5.67	1.99	2.10	
TOTAL	99.10	99.20	99.82	99.30	99.71	100.45	100.06	101.16	
Atomic proportions on the basis of 32 oxygens									
Ti	0.345	0.462	0.425	0.439	0.127	0.237	0.156	0.354	
Al	3.198	3.117	3.454	3.003	2.657	5.084	2.519	3.462	
Cr	12.032	11.857	11.636	11.958	12.932	10.340	13.011	11.692	
Fe ²⁺	7.587	7.405	7.521	7.599	6.981	6.082	7.466	7.614	
Mn	0.086	0.081	0.081	0.082	0.088	0.074	0.087	0.082	
Mg	0.790	1.130	0.913	1.000	1.294	2.235	0.842	0.866	
TOTAL	24.039	24.051	24.030	24.081	24.078	24.051	24.079	24.069	

Table 6.1 continued

Meteorite	MALVERN		M O L T E N O			
	MACR1/02	MACR3/05	MOCR2/03	MOCR2/04	MOCR2/05	MOCR2/08
Sample						
TiO ₂	1.17	0.59	1.19	1.22	0.51	0.87
Al ₂ O ₃	18.23	13.32	11.40	9.32	6.50	8.61
Cr ₂ O ₃	44.19	49.91	52.52	54.60	58.76	56.15
FeO*	33.48	33.27	31.91	32.39	31.33	30.02
MnO	0.26	0.25	0.34	0.36	0.37	0.33
MgO	1.24	0.88	2.14	1.57	1.94	2.48
TOTAL	98.57	98.22	99.50	99.46	99.41	98.46
Atomic proportions on the basis of 32 oxygens						
Ti	0.242	0.126	0.250	0.260	0.110	0.187
Al	5.904	4.447	3.759	3.116	2.202	2.894
Cr	9.600	11.177	11.616	12.247	13.351	12.661
Fe ²⁺	7.693	7.881	7.465	7.685	7.530	7.160
Mn	0.061	0.060	0.081	0.087	0.090	0.080
Mg	0.508	0.371	0.892	0.664	0.831	1.054
TOTAL	24.007	24.062	24.062	24.058	24.113	24.036

Table 6.2. Analyses representative of the ilmenites present in Binda, Bununu, Malvern, and Molteno

Meteorite	BINDA		BUNUNU		MALVERN				MOLTENO		
Sample	BIIL01	BUIL06	BUIL07	MAIL2/08	MAIL2/10	MAIL2/15	MAIL4/06	MOIL1/11	MOIL2/05	MOIL3/05	
TiO ₂	50.26	52.24	51.91	53.28	52.11	52.69	53.77	54.36	54.60	53.33	
Al ₂ O ₃	0.05	0.02	0.05	0.06	0.19	0.06	0.03	0.02	0.02	0.02	
Cr ₂ O ₃	1.73	0.08	0.07	0.12	1.95	0.89	0.11	0.04	0.11	0.05	
FeO*	44.15	46.02	46.26	44.97	44.12	44.90	44.15	43.86	42.60	45.25	
MnO	0.77	0.81	0.80	0.80	0.85	0.83	0.81	0.81	0.87	0.81	
MgO	2.36	0.87	0.81	0.87	1.01	0.77	1.78	0.62	1.79	0.74	
CaO	0.11	0.12	0.10	0.05	0.11	0.15	0.04	0.09	0.10	0.19	
TOTAL	99.43	100.16	100.00	100.15	100.34	100.29	100.69	99.80	100.09	100.39	
Atomic proportions on the basis of 6 oxygens											
Ti	1.907	1.976	1.970	2.003	1.955	1.982	1.999	2.040	2.029	2.003	
Al	0.003	0.001	0.003	0.004	0.011	0.004	0.002	0.001	0.001	0.001	
Cr	0.069	0.003	0.003	0.005	0.077	0.035	0.004	0.002	0.004	0.002	
Fe ²⁺	1.863	1.936	1.952	1.880	1.841	1.878	1.825	1.830	1.760	1.890	
Mn	0.033	0.035	0.034	0.034	0.036	0.035	0.034	0.034	0.036	0.034	
Mg	0.177	0.065	0.061	0.065	0.075	0.057	0.131	0.046	0.132	0.055	
Ca	0.006	0.006	0.005	0.003	0.006	0.008	0.002	0.005	0.005	0.010	
TOTAL	4.057	4.022	4.028	3.993	4.001	3.999	3.998	3.959	3.968	3.995	

Table 6.3. Analyses representative of the metals present in Binda, Bununu, Malvern, and Molteno

BINDA	MALVERN						
	MAM1/03	MAM1/08	MAM2/01	MAM2/17	MAM2/32	MAM4/11K	MAM4/11T
BIM01							
Fe	79.55	96.01	93.31	94.37	93.64	94.32	96.72
Ni	7.79	3.71	5.78	5.24	5.15	4.49	4.52
Co	10.13	0.75	0.64	0.53	0.68	0.77	0.82
TOTAL	97.47	100.47	99.73	100.14	99.47	99.58	102.06
							100.05

BUNUNU		MOLTENO				
BUM01K	BUM04	MOM1/01	MOM1/06	MOM2/01	MOM3/04K	MOM3/04T
Fe	94.29	96.87	93.59	93.65	99.77	95.40
Ni	4.20	2.41	5.13	5.08	0.13	3.68
Co	1.13	0.53	0.81	0.81	0.57	0.65
TOTAL	99.62	99.81	99.53	99.54	100.47	99.73
						100.47
						100.07

K - kamacite; T - co-existing taenite

Table 6.4. Analyses representative of the olivines present in Malvern and Moltano

Meteorite	MALVERN		MOLTENO
Sample	MAOL1/02	MAOL1/03	MOOL4/01
SiO ₂	36.07	33.67	37.40
FeO*	30.71	44.81	27.12
MgO	32.32	19.78	35.13
CaO	0.08	0.07	0.07
TOTAL	99.18	98.33	99.72

Atomic proportions on the basis of 4 oxygens

Si	0.988	1.002	0.998
Fe ²⁺	0.703	1.116	0.605
Mg	1.319	0.878	1.397
Ca	0.002	0.002	0.002
TOTAL	3.012	2.998	3.002
Fo	65.22	44.03	69.77
Fa	34.78	55.97	30.23

Table 6.5. Analyses representative of the plagioclases present in the five achondrites studied

Meteorite	B I N D A					B U N N U				
	BIPL01	BIPL07	BIPL32	BIPL39	BUPL03	BUPL10	BUPL17	BUPL29	BUPL41	BUPL54
Sample										
SiO ₂	44.06	44.51	44.54	43.98	46.44	44.90	45.65	44.90	44.13	44.45
Al ₂ O ₃	35.87	35.31	35.33	35.89	34.24	35.05	34.22	35.09	35.53	35.32
FeO*	0.06	0.06	0.08	0.15	0.14	0.06	0.80	0.07	0.27	0.20
CaO	19.40	19.06	18.59	19.16	17.37	18.37	17.91	18.58	19.39	18.85
Na ₂ O	0.59	0.81	1.04	0.74	1.64	1.07	1.24	0.95	0.63	0.84
K ₂ O	0.03	0.04	0.05	0.04	0.12	0.08	0.08	0.06	0.03	0.04
TOTAL	100.01	99.79	99.63	99.96	99.95	99.53	90.90	99.65	99.98	99.70
Atomic proportions on the basis of 32 oxygens										
Si	8.151	8.246	8.259	8.144	8.550	8.325	8.448	8.316	8.176	8.243
Al	7.822	7.710	7.722	7.833	7.430	7.660	7.464	7.661	7.759	7.721
Fe ²⁺	0.009	0.009	0.012	0.023	0.022	0.009	0.124	0.011	0.042	0.031
Ca	3.846	3.783	3.694	3.802	3.427	3.649	3.551	3.687	3.849	3.746
Na	0.212	0.291	0.374	0.266	0.585	0.385	0.445	0.341	0.226	0.302
K	0.007	0.009	0.012	0.009	0.028	0.019	0.019	0.014	0.007	0.009
TOTAL	20.047	20.049	20.073	20.077	20.042	20.047	20.052	20.031	20.061	20.052
An	94.62	92.64	90.54	93.25	84.81	90.04	88.45	91.21	94.28	92.32
Ab	5.21	7.12	9.17	6.52	14.49	9.49	11.08	8.44	5.54	7.44
Or	0.17	0.23	0.29	0.23	0.70	0.47	0.47	0.35	0.17	0.23

Table 6.5 continued

Meteorite	F R A N K F O R T					M A L V E R N							
	FRPL10	FRPL12	FRPL16	FRPL22	FRPL42	MAPL1/02	MAPL1/04	MAPL1/52	MAPL2/08	MAPL2/10	MAPL2/24		
SiO ₂	44.27	48.58	45.87	45.34	45.16	45.76	46.05	46.78	44.47	48.77	48.19		
Al ₂ O ₃	35.83	32.32	34.04	34.79	34.89	34.62	34.67	33.78	35.17	31.67	32.63		
FeO*	0.10	0.27	0.22	0.13	0.30	0.21	0.19	0.20	0.40	0.73	0.29		
CaO	19.38	16.08	18.37	18.61	18.52	18.23	18.07	17.90	18.88	15.89	16.60		
Na ₂ O	0.72	2.31	1.35	1.18	0.95	0.95	1.03	1.20	0.60	1.90	1.58		
K ₂ O	0.04	0.27	0.10	0.07	0.06	0.05	0.05	0.06	0.02	0.18	0.13		
TOTAL	100.34	99.83	99.95	100.12	99.88	99.82	100.06	99.92	99.54	99.14	99.42		
Atomic proportions on the basis of 32 oxygens													
Si	8.167	8.925	8.477	8.366	8.350	8.445	8.471	8.611	8.260	9.014	8.877		
Al	7.791	6.999	7.415	7.566	7.604	7.531	7.518	7.330	7.700	6.900	7.085		
Fe ²⁺	0.015	0.041	0.034	0.020	0.046	0.032	0.029	0.031	0.062	0.113	0.045		
Ca	3.831	3.166	3.637	3.679	3.669	3.605	3.562	3.531	3.758	3.147	3.277		
Na	0.258	0.823	0.484	0.422	0.341	0.340	0.367	0.428	0.216	0.681	0.564		
K	0.009	0.063	0.024	0.016	0.014	0.012	0.012	0.014	0.005	0.042	0.031		
TOTAL	20.071	20.018	20.070	20.070	20.025	19.965	19.959	19.945	20.000	19.897	19.878		
An	93.49	78.13	87.76	89.35	91.18	91.11	90.38	88.86	94.45	81.31	84.63		
Ab	6.29	20.31	11.67	10.25	8.46	8.59	9.32	10.78	5.43	17.59	14.58		
Or	0.23	1.56	0.57	0.40	0.35	0.30	0.30	0.35	0.12	1.10	0.79		

Table 6.5 continued

Meteorite		M A L V E R N (contd)				M O L T E N O									
Sample	MAPL2/42	MAPL2/58	MAPL4/05	MAPL4/13	MOPL2/18	MOPL2/20	MOPL2/32	MOPL2/38	MOPL4/07	MOPL4/23	MOPL4/27				
SiO ₂	44.66	44.36	46.13	47.91	44.93	44.86	44.30	48.94	49.30	44.68	46.36				
Al ₂ O ₃	35.43	35.27	33.96	32.54	34.69	35.28	35.78	32.02	31.89	35.66	34.41				
FeO*	0.08	0.26	0.07	0.28	0.23	0.10	0.31	0.31	0.26	0.13	0.17				
CaO	18.85	18.92	17.67	16.33	18.26	18.71	18.97	15.05	15.87	18.61	17.28				
Na ₂ O	0.80	0.71	1.33	1.94	1.20	0.98	0.53	2.66	2.13	0.74	1.52				
K ₂ O	0.02	0.02	0.06	0.14	0.02	0.06	0.04	0.23	0.21	0.04	0.07				
TOTAL	99.84	99.54	99.22	99.14	99.33	99.99	99.93	99.21	99.66	99.86	99.81				
Atomic proportions on the basis of 32 oxygens															
Si	8.260	8.240	8.551	8.859	8.353	8.287	8.195	9.021	9.046	8.255	8.539				
Al	7.724	7.722	7.420	7.092	7.602	7.682	7.802	6.957	6.897	7.766	7.471				
Fe ²⁺	0.012	0.040	0.011	0.043	0.036	0.015	0.048	0.048	0.040	0.020	0.026				
Ca	3.736	3.766	3.510	3.236	3.637	3.704	3.760	2.972	3.120	3.684	3.410				
Na	0.287	0.256	0.478	0.696	0.433	0.351	0.190	0.951	0.758	0.265	0.543				
K	0.005	0.005	0.014	0.033	0.005	0.014	0.009	0.054	0.049	0.009	0.016				
TOTAL	20.024	20.029	19.985	19.959	20.065	20.054	20.004	20.003	19.909	19.999	20.005				
An	92.76	93.53	87.70	81.62	89.27	91.02	94.96	74.74	79.45	93.07	85.91				
Ab	7.12	6.35	11.95	17.55	10.62	8.63	4.80	23.90	19.30	6.70	13.68				
Or	0.12	0.12	0.35	0.83	0.12	0.35	0.24	1.36	1.25	0.24	0.41				

Table 6.6. Analyses representative of the pyroxenes present in the five achondrites studied

Meteorite	B I N D A					
Sample	BIPX02	BIPX10	BIPX15	BIPX35	BIPX38H	BIPX38L
SiO ₂	52.52	52.46	52.47	53.60	53.42	52.95
TiO ₂	0.18	0.30	0.36	0.17	0.20	0.27
Al ₂ O ₃	0.55	0.51	0.52	0.54	0.59	0.83
Cr ₂ O ₃	0.25	0.23	0.22	0.24	0.30	0.47
FeO*	20.57	21.94	22.24	20.48	20.28	7.95
MnO	0.60	0.57	0.57	0.64	0.62	0.31
MgO	22.62	21.13	21.72	23.36	23.26	14.94
CaO	1.73	2.35	1.29	1.12	1.32	22.13
TOTAL	99.02	99.49	99.39	100.15	99.99	99.85

Atomic proportions on the basis of 6 oxygens

Si	1.971	1.975	1.974	1.981	1.977	1.971
Ti	0.005	0.008	0.010	0.005	0.006	0.008
Al	0.024	0.023	0.023	0.024	0.026	0.036
Cr	0.007	0.007	0.007	0.007	0.009	0.014
Fe ²⁺	0.646	0.691	0.700	0.633	0.628	0.247
Mn	0.019	0.018	0.018	0.020	0.019	0.010
Mg	1.265	1.185	1.218	1.286	1.283	0.829
Ca	0.070	0.095	0.052	0.044	0.052	0.882
TOTAL	4.008	4.002	4.001	3.999	4.000	3.997
Wo	3.51	4.81	2.64	2.26	2.67	45.06
En	63.89	60.15	61.83	65.51	65.36	42.31
Fs	32.60	35.05	35.53	32.23	31.98	12.63

H - average host phase; L - average exsolved phase; n.d. - not determined

Table 6.6 continued

Meteorite	BUNUNU continued			F R A N K F O R T			
Sample	BUPX96	BUPX97H	BUPX97L	FRPX06	FRPX07	FRPX20	FRPX33
SiO ₂	49.34	51.04	51.46	51.13	51.56	54.55	55.21
TiO ₂	0.22	0.31	0.51	0.28	0.64	0.11	0.07
Al ₂ O ₃	0.27	0.40	0.71	0.89	0.81	0.60	1.03
Cr ₂ O ₃	0.57	0.20	0.40	0.62	0.51	0.56	0.69
FeO*	34.52	27.16	13.00	26.19	23.02	18.62	14.45
MnO	0.86	0.72	0.42	0.75	0.61	0.46	0.42
MgO	13.21	18.05	13.02	15.89	19.49	24.84	27.66
CaO	1.48	1.68	20.29	4.75	3.75	1.24	0.61
TOTAL	100.47	99.56	99.81	100.50	100.39	100.98	100.14

Atomic proportions on the basis of 6 oxygens

Si	1.960	1.969	1.957	1.963	1.946	1.980	1.978
Ti	0.007	0.009	0.015	0.008	0.018	0.003	0.002
Al	0.013	0.018	0.032	0.040	0.036	0.026	0.043
Cr	0.018	0.006	0.012	0.019	0.015	0.016	0.020
Fe ²⁺	1.147	0.876	0.413	0.841	0.727	0.565	0.433
Mn	0.029	0.024	0.014	0.024	0.020	0.014	0.013
Mg	0.782	1.038	0.738	0.909	1.096	1.344	1.477
Ca	0.063	0.069	0.827	0.195	0.152	0.048	0.023
TOTAL	4.018	4.010	4.007	4.000	4.010	3.996	3.989
Wo	3.16	3.50	41.80	10.04	7.68	2.46	1.21
En	39.26	52.32	37.30	46.73	55.52	68.66	76.39
Fs	57.58	44.18	20.90	43.22	36.80	28.88	22.40

Table 6.6 continued

Meteorite	F R A N K F O R T continued					
Sample	FRPX47	FRPX68L	FRPX74	FRPX87	FRPX90	FRPX97
SiO ₂	53.61	50.52	52.69	49.66	51.58	50.84
TiO ₂	0.23	0.50	0.14	1.25	0.07	0.45
Al ₂ O ₃	0.91	1.11	0.75	1.35	0.18	0.48
Cr ₂ O ₃	0.43	0.32	0.58	0.48	0.11	0.32
FeO*	17.46	18.82	20.69	20.76	25.52	21.69
MnO	0.45	0.47	0.46	0.56	1.00	0.76
MgO	26.10	9.97	23.40	12.04	17.73	13.19
CaO	1.07	19.64	1.56	14.75	3.98	13.14
TOTAL	100.26	101.35	100.27	100.85	100.17	100.87

Atomic proportions on the basis of 6 oxygens

Si	1.953	1.941	1.953	1.913	1.976	1.954
Ti	0.006	0.014	0.004	0.036	0.002	0.013
Al	0.039	0.050	0.033	0.061	0.008	0.022
Cr	0.012	0.010	0.017	0.015	0.003	0.010
Fe ²⁺	0.532	0.605	0.641	0.669	0.818	0.697
Mn	0.014	0.015	0.014	0.018	0.032	0.025
Mg	1.417	0.571	1.293	0.691	1.012	0.756
Ca	0.042	0.808	0.062	0.609	0.163	0.541
TOTAL	4.015	4.015	4.018	4.013	4.016	4.017
Wo	2.10	40.75	3.10	30.92	8.20	27.14
En	71.18	28.77	64.76	35.11	50.78	37.89
Fs	26.72	30.48	32.13	33.97	41.02	34.97

Table 6.6 continued

Meteorite	M A L V E R N						
Sample	MAOP1/41	MAOP1/58	MAOP1/63	MAOP2/03	MAOP3/04	MAOP3/31	MAOP3/33
SiO ₂	53.44	56.50	52.24	53.79	53.14	52.88	54.88
TiO ₂	0.21	0.08	0.27	0.10	0.14	0.13	0.07
Al ₂ O ₃	0.66	0.62	0.56	1.16	0.99	1.29	0.58
Cr ₂ O ₃	0.56	n.d.	n.d.	0.74	n.d.	0.92	0.52
FeO*	20.90	11.51	25.10	16.37	19.12	18.12	14.06
MnO	0.64	0.31	0.72	0.45	0.10	0.55	0.41
MgO	21.74	29.20	17.94	26.40	23.92	24.58	28.55
CaO	1.78	0.76	1.74	1.29	1.86	1.62	0.80
TOTAL	99.93	98.98	98.57	100.30	99.27	100.09	99.87

Atomic proportions on the basis of 6 oxygens

Si	1.987	2.013	2.008	1.951	1.969	1.943	1.972
Ti	0.006	0.002	0.008	0.003	0.004	0.004	0.002
Al	0.029	0.026	0.025	0.050	0.043	0.056	0.025
Cr	0.016	---	---	0.021	---	0.027	0.015
Fe ²⁺	0.650	0.343	0.807	0.496	0.592	0.557	0.422
Mn	0.020	0.009	0.023	0.014	0.003	0.017	0.012
Mg	1.205	1.550	1.028	1.427	1.321	1.346	1.529
Ca	0.071	0.029	0.072	0.050	0.074	0.064	0.031
TOTAL	3.984	3.972	3.971	4.011	4.006	4.012	4.007
Wo	3.68	1.51	3.76	2.54	3.72	3.24	1.55
En	62.56	80.65	53.91	72.30	66.47	68.44	77.13
Fs	33.75	17.84	42.33	25.16	29.82	28.31	21.32

Table 6.6 continued

Meteorite	M A L V E R N continued						
Sample	MAPG1/02	MAOP1/14	MAPG1/23	MAPG1/25	MAPG1/35	MAOP1/71	MAPG3/10
SiO ₂	51.58	53.54	49.40	48.15	50.11	50.69	49.33
TiO ₂	0.24	0.20	0.38	0.51	0.50	0.51	0.46
Al ₂ O ₃	0.99	0.60	0.95	1.41	1.62	1.03	0.93
Cr ₂ O ₃	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.50
FeO*	25.16	21.68	28.39	26.85	26.24	27.38	29.35
MnO	0.77	0.69	0.84	0.84	0.74	0.79	0.91
MgO	17.50	20.67	13.72	9.06	15.90	15.16	12.46
CaO	3.54	2.95	5.79	12.53	4.45	3.82	5.95
TOTAL	99.78	100.33	99.47	99.35	99.56	99.38	99.89

Atomic proportions on the basis of 6 oxygens

Si	1.973	1.994	1.948	1.930	1.941	1.972	1.949
Ti	0.007	0.006	0.011	0.015	0.015	0.015	0.014
Al	0.045	0.026	0.044	0.067	0.074	0.047	0.043
Cr	---	---	---	---	---	---	0.016
Fe ²⁺	0.805	0.675	0.936	0.900	0.850	0.891	0.970
Mn	0.025	0.022	0.028	0.029	0.024	0.026	0.030
Mg	0.998	1.147	0.806	0.541	0.918	0.879	0.734
Ca	0.145	0.118	0.245	0.538	0.185	0.159	0.252
TOTAL	3.998	3.987	4.019	4.021	4.007	3.989	4.008
Wo	7.45	6.07	12.31	27.19	9.46	8.25	12.88
En	51.22	59.13	40.57	27.34	47.01	45.56	37.52
Fs	41.33	34.80	47.11	45.47	43.53	46.18	49.60

Table 6.6 continued

Meteorite	MALVERN	M O L T E N O				
Sample	MAGP3/14	MOPX2/01	MOPX2/08	MOPX2/23	MOPX2/36	MOPX2/51
SiO ₂	48.80	55.32	52.05	53.15	56.11	48.23
TiO ₂	0.81	0.12	0.31	0.18	0.03	0.37
Al ₂ O ₃	0.90	0.71	0.38	0.65	0.45	0.41
Cr ₂ O ₃	0.31	0.39	0.22	0.44	0.68	0.20
FeO*	30.75	13.26	24.82	19.91	11.37	36.76
MnO	0.92	0.44	0.72	0.64	0.37	0.99
MgO	10.08	28.59	20.09	23.12	30.32	8.35
CaO	7.69	1.26	1.06	1.77	0.46	4.52
TOTAL	100.26	100.09	99.65	99.86	99.79	99.83

Atomic proportions on the basis of 6 oxygens

Si	1.945	1.976	1.977	1.971	1.988	1.971
Ti	0.024	0.003	0.009	0.005	0.001	0.011
Al	0.042	0.030	0.017	0.028	0.019	0.020
Cr	0.010	0.011	0.007	0.013	0.019	0.006
Fe ²⁺	1.025	0.396	0.789	0.618	0.337	1.256
Mn	0.031	0.013	0.023	0.020	0.011	0.034
Mg	0.599	1.522	1.137	1.278	1.601	0.508
Ca	0.328	0.048	0.043	0.070	0.017	0.198
TOTAL	4.005	4.000	4.002	4.003	3.993	4.005
Wo	16.82	2.45	2.19	3.58	0.89	10.08
En	30.67	77.40	57.76	65.01	81.88	25.91
Fs	52.51	20.15	40.05	31.41	17.23	64.01

Table 6.7. Analyses representative of the troilites present in Malvern and Molteno

	M A L V E R N		M O L T E N O		
	MATR1/04	MATR1/09	MOTR2/01	MOTR2/04	MOTR4/01
Fe	62.23	62.53	62.76	62.61	62.49
S	37.21	36.36	36.41	36.52	36.64
Ni	0.06	0.06			
Co	0.07	0.05			
TOTAL	99.57	99.00	99.17	99.13	99.13
Fe : S (atomic)	0.96	0.99	0.99	0.98	0.98

Table 6.8. Analyses representative of the glasses present in Bununu, Malvern, and Molteno

Meteorite	B U N U N U				M A L V E R N							
	BUGF01	BUGF03	BUGF11		MAGF1/02	MAGF1/10	MAGF1/21M	MAGF1/21C	MAGF1/24	MAGF2/05	MAGF2/14	MAGF3/08
SiO ₂	49.52	47.51	51.07		48.61	48.95	54.69	46.94	47.43	48.89	47.16	48.24
TiO ₂	0.58	0.64	0.43		0.64	0.46	1.46	0.84	0.57	0.60	0.39	0.60
Al ₂ O ₃	10.16	12.19	7.95		11.26	9.82	17.48	9.67	10.97	11.25	9.90	6.48
Cr ₂ O ₃	0.56	0.42	0.83		0.47	0.56	0.11	0.44	0.47	0.49	0.55	0.36
FeO*	17.76	19.16	17.11		18.19	20.64	11.94	23.57	19.62	18.36	19.81	23.60
MnO	0.45	0.49	0.47		0.44	0.53	0.28	0.55	0.52	0.56	0.52	0.68
MgO	12.77	9.82	16.29		10.95	12.34	3.51	8.58	11.01	10.52	13.10	11.41
CaO	8.07	10.07	6.31		8.59	7.09	10.22	9.10	8.59	8.89	7.25	7.90
Na ₂ O	0.35	0.25	0.14		0.16	0.14	0.36	0.21	0.16	0.15	0.07	0.15
K ₂ O	0.03	0.04	0.14		0.31	0.21	0.03	0.02	0.34	0.32	0.18	0.07
S	--	--	--		--	--	--	--	--	--	--	--
TOTAL	100.25	100.59	100.74		99.62	100.74	100.08	99.92	99.68	100.03	98.93	99.49

M - matrix; C - 'crystals' (see text)

Table 6.8 continued

Meteorite	M O L T E N O							
	Sample	MOGF1/01	MOGF1/15	MOGF1/16	MOGF2/01	MOGF2/03	MOGF2/04	MOGF3/03
	SiO ₂	49.20	49.17	49.04	49.65	63.64	44.60	49.23
	TiO ₂	0.70	0.58	0.75	0.62	4.37	3.49	0.72
	Al ₂ O ₃	12.85	10.42	14.21	10.43	0.15	12.24	13.42
	Cr ₂ O ₃	0.41	0.42	0.25	0.59	0.05	0.85	0.32
	FeO*	17.32	18.99	17.36	17.37	14.53	13.83	17.67
	MnO	0.49	0.50	0.47	0.45	0.03	0.33	0.49
	MgO	8.75	10.69	6.67	12.65	0.81	11.24	7.33
	CaO	9.58	8.38	10.56	8.12	4.68	7.34	10.53
	Na ₂ O	0.41	0.35	0.64	0.34	0.00	0.44	0.33
	K ₂ O	0.04	0.04	0.02	0.03	0.01	0.06	0.51
	S	--	--	--	--	11.92	7.01	--
	TOTAL	99.75	99.54	99.97	100.25	100.19	101.43	100.55

Table 6.9. Analyses representative of the glassy microbreccias and devitrified glasses present in the five achondrites studied

Meteorite	B I N D A			B U N U N U			F R A N K F O R T		M A L V E R N		
	BIMBR01	BIMBR02	BIMBR09	BUMBR05	BUMBR10	BUMBR12	FRMBR01		MAMBR2/05	MAMBR2/08	MAMBR2/22
SiO ₂	50.47	50.72	49.19	49.63	47.29	47.49	50.97		47.04	48.73	48.07
TiO ₂	0.17	0.21	0.10	0.57	0.25	0.24	0.26		0.46	0.66	0.43
Al ₂ O ₃	10.80	6.18	15.27	10.22	12.07	18.16	9.26		12.73	12.08	11.59
Cr ₂ O ₃	0.30	0.19	0.10	0.54	0.22	0.20	0.49		0.49	0.40	0.57
FeO*	15.78	18.82	14.28	18.14	19.23	14.33	17.20		17.36	18.84	17.69
MnO	0.45	0.50	0.31	0.47	0.50	0.39	0.44		0.44	0.45	0.46
MgO	16.63	19.42	12.93	12.22	7.46	6.05	16.15		12.04	10.13	12.10
CaO	7.18	3.75	8.43	8.15	11.92	11.55	6.41		8.03	8.06	7.75
Na ₂ O	0.17	0.11	0.15	0.35	0.39	0.71	0.46		0.79	0.73	0.63
K ₂ O	0.01	0.01	0.01	0.03	0.03	0.04	0.06		0.08	0.08	0.10
TOTAL	101.96	99.91	100.77	100.32	99.36	99.16	101.70		99.46	100.16	99.39

Table 6.9 continued

Meteorite	M A L V E R N					M O L T E N O			
	MANBR3/03	MANBR3/23	MANBR3/24	MALF1/09	MALF2/01	MOMBR1/01	MOMBR1/07	MOMBR2/05	MOMBR4/01
Sample									
SiO ₂	48.41	48.14	48.71	48.72	47.02	49.03	49.01	48.77	51.77
TiO ₂	0.43	0.62	0.41	0.65	0.78	0.70	0.66	0.25	1.53
Al ₂ O ₃	10.58	10.30	10.79	12.69	16.16	12.43	10.67	12.43	15.01
Cr ₂ O ₃	0.54	0.56	0.57	0.55	0.08	0.42	0.53	0.59	0.12
FeO*	18.16	19.40	16.82	16.90	16.82	17.95	18.47	13.55	15.08
MnO	0.49	0.50	0.45	0.47	0.47	0.49	0.41	0.39	0.32
MgO	12.75	11.70	13.35	10.22	6.45	8.69	11.17	15.04	4.38
CaO	7.75	8.25	8.43	8.83	11.19	9.37	8.52	7.57	10.80
Na ₂ O	0.68	0.35	0.37	0.90	0.43	0.42	0.35	0.77	0.75
K ₂ O	0.11	0.15	0.12	0.07	0.03	0.04	0.04	0.08	0.06
TOTAL	99.90	99.97	100.02	100.00	99.43	99.54	99.83	99.44	99.82

Table 6.10. CIPW norms, expressed both as cation % and weight %, calculated for the analyses of glasses presented in Table 6.8

Meteorite	B U N U N U					
Sample	BUGF01		BUGF03		BUGF11	
	Cation %	Weight %	Cation %	Weight %	Cation %	Weight %
Qz					0.15	0.16
Or	0.18	0.18	0.24	0.24	0.83	0.83
Pl	29.75	29.02	35.21	34.14	21.98	21.84
(Ab)	3.20	2.96	2.31	2.12	1.26	1.18
(An)	26.55	26.06	32.90	32.02	20.72	20.65
Wo						
Di	11.39	11.56	14.74	15.02	8.55	8.74
(Wo)	5.69	5.83	7.37	7.49	4.28	4.45
(En)	3.22	2.86	3.55	3.11	2.71	2.43
(Fs)	2.47	2.87	3.83	4.41	1.57	1.85
Hy	55.77	56.12	42.05	42.94	66.97	67.15
(En)	31.58	27.97	20.23	17.76	42.42	38.14
(Fs)	24.19	28.15	21.82	25.18	24.55	29.01
Ol	1.46	1.44	6.37	6.44		
(Fo)	0.83	0.68	3.06	2.51		
(Fa)	0.63	0.76	3.30	3.93		
Cm	0.63	0.82	0.47	0.62	0.91	1.22
Il	0.82	1.10	0.92	1.22	0.60	0.82
Sp						
Py						
SALIC	29.93	29.20	35.45	34.37	22.96	22.83
FEMIC	70.07	71.05	64.55	66.22	77.04	77.92
TOTAL	100.00	100.26	100.00	100.60	100.00	100.75

M - matrix; C - 'crystals' (see text)

Table 6.10 continued

Meteorite		M A L V E R N				
Sample	MAGF1/02		MAGF1/10		MAGF1/21M	
	Cation %	Weight %	Cation %	Weight %	Cation %	Weight %
Qz					16.68	17.29
Or	1.89	1.83	1.27	1.24	0.18	0.18
Pl	31.53	30.44	27.42	26.73	51.30	49.04
(Ab)	1.48	1.35	1.29	1.18	3.37	3.05
(An)	30.05	29.09	26.14	25.55	47.93	45.99
Wo						
Di	11.18	11.26	7.88	8.02	3.93	4.01
(Wo)	5.59	5.65	3.94	4.02	1.96	1.97
(En)	2.92	2.55	2.04	1.80	0.72	0.62
(Fs)	2.67	3.06	1.90	2.20	1.25	1.42
Hy	53.28	53.52	58.40	59.30	25.66	26.64
(En)	27.84	24.32	30.23	26.66	9.38	8.12
(Fs)	25.45	29.21	28.17	32.65	16.28	18.52
Ol	0.67	0.66	3.74	3.75		
(Fo)	0.35	0.28	1.94	1.60		
(Fa)	0.32	0.38	1.81	2.16		
Cm	0.53	0.69	0.63	0.82	0.13	0.16
Il	0.92	1.22	0.66	0.87	2.12	2.77
Sp						
Py						
SALIC	33.42	32.28	28.69	27.97	68.16	66.50
FEMIC	66.58	67.35	71.31	72.78	31.84	33.58
TOTAL	100.00	99.63	100.00	100.75	100.00	100.08

Table 6.10 continued

Meteorite		M A L V E R N continued				
Sample	MAGF1/21C		MAGF1/24		MAGF2/05	
	Cation %	Weight %	Cation %	Weight %	Cation %	Weight %
Qz					0.12	0.12
Or	0.12	0.12	2.08	2.01	1.95	1.89
Pl	28.74	27.16	30.67	29.56	31.37	30.35
(Ab)	1.99	1.78	1.49	1.35	1.39	1.27
(An)	26.75	25.38	29.19	28.21	29.98	29.08
Wo						
Di	16.66	16.73	11.92	12.02	12.39	12.53
(Wo)	8.33	8.25	5.96	6.01	6.20	6.27
(En)	3.31	2.84	3.00	2.61	3.15	2.75
(Fs)	5.02	5.64	2.96	3.40	3.05	3.51
Hy	47.61	48.47	46.09	46.46	52.75	53.28
(En)	18.93	16.21	23.17	20.20	26.80	23.45
(Fs)	28.68	32.26	22.92	26.26	25.95	29.83
Ol	5.12	5.21	7.88	7.85		
(Fo)	2.04	1.63	3.96	3.23		
(Fa)	3.09	3.58	3.92	4.63		
Cm	0.51	0.65	0.53	0.69	0.55	0.72
Il	1.23	1.60	0.82	1.08	0.86	1.14
Sp						
Py						
SALIC	28.86	27.28	32.75	31.57	33.44	32.36
FEMIC	71.14	72.65	67.25	68.11	66.56	67.67
TOTAL	100.00	99.93	100.00	99.69	100.00	100.04

Table 6.10 continued

Meteorite	MALVERN continued				MOLTENO	
Sample	MAGF2/14		MAGF3/08		MOGF1/01	
	Cation %	Weight %	Cation %	Weight %	Cation %	Weight %
Qz					1.91	2.00
Or	1.10	1.06	0.43	0.41	0.24	0.24
Pl	27.76	26.76	19.07	18.07	38.10	36.57
(Ab)	0.65	0.59	1.41	1.27	3.81	3.47
(An)	27.11	26.17	17.65	16.80	34.29	33.10
Wo						
Di	8.12	8.14	18.82	18.79	11.95	12.08
(Wo)	4.06	4.09	9.41	9.35	5.98	6.02
(En)	2.20	1.92	4.36	3.74	2.86	2.49
(Fs)	1.86	2.13	5.05	5.70	3.12	3.57
Hy	52.10	51.89	55.37	55.56	46.31	46.94
(En)	28.24	24.59	25.64	22.02	22.16	19.30
(Fs)	23.86	27.30	29.73	33.54	24.15	27.64
Ol	9.72	9.53	5.02	4.99		
(Fo)	5.27	4.29	2.32	1.86		
(Fa)	4.45	5.25	2.69	3.13		
Cm	0.63	0.81	0.42	0.53	0.47	0.60
Il	0.56	0.74	0.88	1.14	1.01	1.33
Sp						
Py						
SALIC	28.86	27.82	19.50	18.48	40.26	38.80
FEMIC	71.14	71.11	80.50	81.01	59.74	60.95
TOTAL	100.00	98.94	100.00	99.50	100.00	99.76

Table 6.10 continued

Meteorite		MOLTENO continued				
Sample	MOGF1/15		MOGF1/16		MOGF2/01	
	Cation %	Weight %	Cation %	Weight %	Cation %	Weight %
Qz	0.57	0.59	1.91	1.99		
Or	0.24	0.24	0.12	0.12	0.18	0.18
Pl	30.98	29.70	43.19	41.26	30.45	29.72
(Ab)	3.26	2.96	5.97	5.42	3.11	2.88
(An)	27.72	26.74	37.22	35.84	27.34	26.84
Wo						
Di	12.30	12.38	13.75	13.99	10.95	11.12
(Wo)	6.15	6.19	6.87	6.91	5.47	5.61
(En)	3.10	2.70	2.82	2.45	3.12	2.77
(Fs)	3.05	3.49	4.05	4.62	2.35	2.74
Hy	54.59	54.92	39.66	40.83	56.88	57.19
(En)	27.50	23.93	16.30	14.16	32.44	28.73
(Fs)	27.10	30.99	23.36	26.67	24.44	28.45
Ol					0.01	0.01
(Fo)					0.01	0.01
(Fa)						
Cm	0.48	0.62	0.29	0.37	0.66	0.87
Il	0.84	1.10	1.08	1.42	0.88	1.18
Sp						
Py						
SALIC	31.79	30.53	45.22	43.37	30.63	29.90
FEMIC	68.21	69.01	54.78	56.61	69.37	70.36
TOTAL	100.00	99.55	100.00	99.98	100.00	100.26

Table 6.10 continued

Meteorite		MOLTENO continued				
Sample	MOGF2/03*		MOGF2/04*		MOGF3/03	
	Cation %	Weight %	Cation %	Weight %	Cation %	Weight %
Qz	53.10	57.30	7.20	8.13	1.30	1.36
Or	0.06	0.06	0.34	0.35	3.11	3.01
Pl	0.41	0.41	33.68	34.97	37.80	36.42
(Ab)			3.78	3.72	3.06	2.79
(An)	0.41	0.41	29.90	31.25	34.74	33.63
Wo	2.63	2.74				
Di	4.47	4.35	3.96	4.09	15.38	15.69
(Wo)	2.24	2.33	1.98	2.16	7.69	7.77
(En)	2.24	2.02	1.74	1.64	3.30	2.88
(Fs)			0.24	0.30	4.39	5.04
Hy			31.82	31.14	41.00	42.23
(En)			27.95	26.35	17.60	15.37
(Fs)			3.87	4.79	23.40	26.86
Ol						
(Fo)						
(Fa)						
Cm	0.07	0.09	0.89	1.25	0.36	0.47
Il	1.82	2.49	4.65	6.63	1.04	1.37
Sp	6.40	7.51				
Py	10.35	22.30	5.82	13.11		
SALIC	53.56	57.77	41.22	43.45	42.22	40.80
FEMIC	25.74	39.48	47.14	56.23	57.78	59.76
TOTAL	79.30	97.25	88.36	99.69	100.00	100.56

* The cation % totals of these S-bearing glasses are low by the calculated atomic % of S present; the weight % totals are low by the amounts of O equivalent to S in the original analyses.

Table 6.11. CIPW norms, expressed both as cation % and weight %, calculated for the analyses of glassy microbreccias and devitrified glasses presented in Table 6.9

Meteorite		B I N D A				
Sample	BIMBR01		BIMBR02		BIMBR09	
	Cation %	Weight %	Cation %	Weight %	Cation %	Weight %
Qz						
Or	0.06	0.06	0.06	0.06	0.06	0.06
Pl	29.66	30.11	17.38	17.27	42.24	42.23
(Ab)	1.50	1.44	0.99	0.93	1.34	1.27
(An)	28.16	28.68	16.39	16.34	40.90	40.96
Di	5.46	5.68	1.82	1.85	0.69	0.71
(Wo)	2.73	2.90	0.91	0.95	0.34	0.36
(En)	1.77	1.63	0.59	0.53	0.21	0.19
(Fs)	0.95	1.15	0.32	0.38	0.13	0.16
Hy	57.28	58.41	73.61	73.59	54.09	54.80
(En)	37.25	34.22	47.48	42.71	33.24	30.04
(Fs)	20.03	24.19	26.13	30.89	20.85	24.76
Ol	6.99	6.94	6.63	6.46	2.67	2.64
(Fo)	4.54	3.90	4.28	3.60	1.64	1.38
(Fa)	2.44	3.04	2.35	2.87	1.03	1.26
Cm	0.32	0.44	0.21	0.28	0.11	0.15
Il	0.23	0.32	0.29	0.40	0.14	0.19
SALIC	29.72	30.17	17.44	17.33	42.30	42.29
FEMIC	70.28	71.79	82.56	82.59	57.70	58.48
TOTAL	100.00	101.96	100.00	99.92	100.00	100.77

Table 6.11 continued

Meteorite		B U N U N U				
Sample	BUMBR05		BUMBR10		BUMBR12	
	Cation %	Weight %	Cation %	Weight %	Cation %	Weight %
Qz						
Or	0.18	0.18	0.19	0.18	0.24	0.24
Pl	29.99	29.19	36.25	34.39	54.44	52.25
(Ab)	3.21	2.96	3.67	3.30	6.60	6.01
(An)	26.78	26.23	32.58	31.09	47.85	46.25
Di	11.60	11.78	23.50	23.71	9.15	9.32
(Wo)	5.80	5.93	11.75	11.71	4.57	4.62
(En)	3.19	2.82	4.78	4.11	1.96	1.71
(Fs)	2.61	3.03	6.97	7.89	2.62	3.00
Hy	56.65	57.14	33.83	34.56	34.93	35.93
(En)	31.14	27.51	13.75	11.84	14.95	13.03
(Fs)	25.52	29.63	20.08	22.72	19.98	22.90
Ol	0.16	0.16	5.62	5.72	0.66	0.67
(Fo)	0.09	0.07	2.28	1.84	0.28	0.23
(Fa)	0.07	0.09	3.33	3.88	0.38	0.44
Cm	0.61	0.80	0.25	0.32	0.23	0.29
Il	0.81	1.08	0.36	0.47	0.35	0.46
SALIC	30.17	29.37	36.43	34.57	54.69	52.49
FEMIC	69.83	70.96	63.57	64.79	45.31	46.67
TOTAL	100.00	100.33	100.00	99.36	100.00	99.16

Table 6.11 continued

Meteorite	FRANKFORT		M A L V E R N			
Sample	FRMBR01		MAMBR2/05		MAMBR2/08	
	Cation %	Weight %	Cation %	Weight %	Cation %	Weight %
Qz						
Or	0.35	0.35	0.48	0.47	0.49	0.47
Pl	26.87	26.92	38.81	37.64	36.97	35.63
(Ab)	4.09	3.89	7.24	6.68	6.73	6.18
(An)	22.78	23.02	31.58	30.95	30.24	29.45
Di	6.95	7.20	7.25	7.36	8.66	8.81
(Wo)	3.47	3.66	3.63	3.71	4.33	4.40
(En)	2.18	1.98	2.01	1.78	2.14	1.88
(Fs)	1.30	1.56	1.61	1.87	2.19	2.53
Hy	58.85	59.96	36.82	37.10	48.51	49.40
(En)	36.86	33.60	20.46	18.09	23.95	21.04
(Fs)	22.00	26.36	16.36	19.01	24.56	28.35
Ol	6.09	6.06	15.44	15.30	3.99	4.02
(Fo)	3.81	3.25	8.58	7.09	1.97	1.62
(Fa)	2.28	2.81	6.86	8.21	2.02	2.40
Cm	0.53	0.72	0.55	0.72	0.45	0.59
Il	0.36	0.49	0.65	0.87	0.94	1.25
SALIC	27.22	27.27	39.29	38.11	37.45	36.10
FEMIC	72.78	74.43	60.71	61.36	62.55	64.07
TOTAL	100.00	101.70	100.00	99.47	100.00	100.17

Table 6.11 continued

Meteorite		MALVERN continued				
Sample	MAMBR2/22		MAMBR3/03		MAMBR3/23	
	Cation %	Weight %	Cation %	Weight %	Cation %	Weight %
Qz						
Or	0.611	0.59	0.66	0.65	0.91	0.89
Pl	35.00	33.83	32.19	31.25	30.07	29.05
(Ab)	5.80	5.33	6.22	5.75	3.23	2.96
(An)	29.21	28.50	25.97	25.49	26.84	26.09
Di	8.15	8.25	10.56	10.73	12.21	12.35
(Wo)	4.08	4.15	5.28	5.41	6.10	6.20
(En)	2.25	1.98	2.95	2.61	3.19	2.80
(Fs)	1.83	2.11	2.33	2.72	2.92	3.36
Hy	46.14	46.33	44.50	44.88	48.60	49.02
(En)	25.47	22.42	24.82	21.98	25.37	22.26
(Fs)	20.67	23.91	19.68	22.90	23.22	26.77
Ol	8.84	8.73	10.88	10.79	6.69	6.66
(Fo)	4.88	4.02	6.07	5.02	3.50	2.86
(Fa)	3.96	4.72	4.81	5.77	3.20	3.80
Cm	0.64	0.84	0.60	0.80	0.63	0.82
Il	0.61	0.82	0.61	0.82	0.89	1.18
SALIC	35.61	34.42	32.85	31.90	30.98	29.94
FEMIC	64.39	64.97	67.15	68.01	69.02	70.04
TOTAL	100.00	99.39	100.00	99.91	100.00	99.98

Table 6.11 continued

Meteorite		MALVERN continued				
Sample	MAMBR3/24		MALF1/09		MALF2/01	
	Cation %	Weight %	Cation %	Weight %	Cation %	Weight %
Qz						
Or	0.72	0.71	0.42	0.41	0.18	0.18
Pl	31.20	30.56	39.31	37.99	47.85	45.71
(Ab)	3.37	3.13	8.26	7.62	4.02	3.64
(An)	27.83	27.43	31.05	30.38	43.83	42.08
Di	11.68	11.88	10.98	11.18	11.20	11.36
(Wo)	5.84	6.01	5.49	5.61	5.60	5.61
(En)	3.44	3.06	2.88	2.54	2.29	1.99
(Fs)	2.40	2.81	2.61	3.03	3.31	3.76
Hy	47.66	47.86	42.46	43.09	39.16	40.19
(En)	28.05	24.94	22.26	19.65	16.05	13.90
(Fs)	19.61	22.92	20.20	23.44	23.11	26.30
Ol	7.52	7.40	5.29	5.29	0.38	0.39
(Fo)	4.43	3.68	2.77	2.29	0.16	0.13
(Fa)	3.10	3.73	2.52	3.01	0.23	0.26
Cm	0.64	0.84	0.62	0.81	0.09	0.12
Il	0.58	0.78	0.93	1.23	1.13	1.48
SALIC	31.91	31.27	39.73	38.41	48.04	45.89
FEMIC	68.09	68.76	60.27	61.60	51.96	53.54
TOTAL	100.00	100.03	100.00	100.01	100.00	99.43

Table 6.11 continued

Meteorite		M O L T E N O				
Sample	MOMBR1/01		MOMBR1/07		MOMBR2/05	
	Cation %	Weight %	Cation %	Weight %	Cation %	Weight %
Qz	1.75	1.82	0.03	0.03		
Or	0.25	0.24	0.24	0.24	0.47	0.47
Pl	37.11	35.47	31.50	30.39	37.18	36.74
(Ab)	3.92	3.55	3.24	2.96	6.92	6.52
(An)	33.19	31.91	28.26	27.42	30.26	30.22
Di	12.12	12.22	12.23	12.35	5.87	5.98
(Wo)	6.06	6.08	6.12	6.20	2.94	3.06
(En)	2.84	2.46	3.21	2.81	1.96	1.76
(Fs)	3.23	3.68	2.91	3.35	0.98	1.16
Hy	47.27	47.86	54.45	54.79	43.49	43.30
(En)	22.12	19.18	28.56	25.01	28.96	26.10
(Fs)	25.16	28.68	25.88	29.78	14.52	17.20
Ol					11.99	11.61
(Fo)					7.99	6.72
(Fa)					4.00	4.88
Cm	0.48	0.62	0.60	0.78	0.65	0.87
Il	1.01	1.33	0.95	1.25	0.35	0.47
SALIC	39.11	37.52	31.77	30.66	37.65	37.21
FEMIC	60.89	62.03	68.23	69.18	62.35	62.23
TOTAL	100.00	99.55	100.00	99.84	100.00	99.44

Table 6.11 continued

Meteorite	MOLTENO continued	
Sample	MOMBR4/01	
	Cation %	Weight %
Qz	9.02	9.31
Or	0.37	0.35
Pl	46.18	43.76
(Ab)	7.04	6.35
(An)	39.14	37.41
Di	13.53	13.76
(Wo)	6.77	6.75
(En)	2.43	2.09
(Fs)	4.34	4.92
Hy	28.52	29.55
(En)	10.22	8.82
(Fs)	18.30	20.74
Ol		
(Fo)		
(Fa)		
Cm	0.14	0.18
Il	2.23	2.91
SALIC	55.58	53.43
FEMIC	44.42	46.40
TOTAL	100.00	99.83

Table 6.12. Ranges present in the chromites analyzed in the five achondrites studied

	BINDA	BUNUNU	FRANKFORT	MALVERN	MOLTENO
TiO ₂	1.04- 3.82	0.21- 3.68	0.33- 2.97	0.36- 5.33	0.18- 6.05
Al ₂ O ₃	8.71-13.01	5.54-19.04	6.49-13.16	4.88-18.23	6.03-12.52
Cr ₂ O ₃	50.40-54.64	43.26-59.48	51.56-60.55	44.19-59.16	46.05-59.03
FeO*	30.68-33.01	24.02-34.74	30.59-34.05	30.63-36.25	24.07-35.21
MnO	0.32- 0.36	0.28- 0.39	0.33- 0.37	0.23- 0.31	0.31- 0.37
MgO	1.41- 3.28	1.39- 7.01	1.94- 3.50	0.61- 1.78	1.40- 6.61

Table 6.13. Ranges present in the ilmenites analyzed in Binda, Bununu, Malvern, and Molteno

	BINDA	BUNUNU	MALVERN	MOLTENO
TiO ₂	49.50-50.26	51.48-53.49	47.79-54.82	53.33-55.19
Al ₂ O ₃	0.05- 0.88	0.01- 0.22	0.00- 3.46	0.01- 0.29
Cr ₂ O ₃	0.55- 2.53	0.05- 0.14	0.02- 1.95	0.04- 0.61
FeO*	43.02-44.15	45.07-46.85	39.15-47.38	40.99-45.25
MnO	0.74- 0.79	0.61- 0.82	0.23- 0.92	0.70- 1.16
MgO	2.36- 2.67	0.44- 1.88	0.51-10.15	0.23- 2.54
CaO	0.11- 0.29	0.06- 0.18	0.00- 0.34	0.02- 0.33

Table 6.14. Ranges present in the metals analyzed in Bununu, Malvern, and Molteno

	BUNUNU	MALVERN	MOLTENO
Fe	57.40-96.87	47.32-98.83	46.45-99.77
Ni	1.97-38.45	3.18-52.53	0.13-54.48
Co	0.37- 3.64	0.20- 0.92	0.17- 2.17

Table 6.15. Ranges present in the olivines analyzed in Malvern and Molteno

	MALVERN	MOLTENO
SiO ₂	33.67-36.54	37.10-37.49
FeO*	30.71-44.81	26.80-28.46
MgO	19.78-32.45	34.10-35.31
CaO	0.05- 0.11	0.05- 0.14

Table 6.16. Ranges present in the plagioclases analyzed in the five achondrites studied

	BINDA	BUNUNU	FRANKFORT	MALVERN	MOLTENO
SiO ₂	43.61-44.87	43.43-48.23	43.59-50.44	43.96-50.27	43.69-50.28
Al ₂ O ₃	35.07-36.11	31.99-36.26	32.11-36.38	30.65-35.67	30.83-36.13
FeO*	0.03- 0.15	0.04- 2.17	0.06- 1.27	0.07- 1.41	0.04- 0.59
CaO	18.59-19.42	15.87-19.62	15.82-19.90	15.00-19.36	14.26-19.67
Na ₂ O	0.59- 1.04	0.53- 1.87	0.47- 2.31	0.45- 2.19	0.53- 2.66
K ₂ O	0.02- 0.05	0.01- 0.18	0.03- 0.35	0.00- 0.26	0.00- 0.36

Table 6.17. Ranges present in the pyroxenes analyzed in the five achondrites studied

	BINDA	BUNUNU	FRANKFORT	MALVERN	MOLTENO
SiO ₂	51.71-53.60	48.50-56.19	48.34-55.67	46.30-57.65	48.23-56.11
TiO ₂	0.17- 0.66	0.04- 1.25	0.03- 1.25	0.02- 0.96	0.03- 0.67
Al ₂ O ₃	0.46- 1.14	0.17- 1.34	0.18- 2.24	0.14- 4.90	0.18- 2.06
Cr ₂ O ₃	0.22- 0.48	0.09- 0.88	0.10- 1.24	0.22- 1.22	0.11- 0.79
FeO*	7.52-23.28	9.35-34.52	14.45-36.42	8.29-35.63	11.37-36.90
MnO	0.27- 0.69	0.25- 0.93	0.34- 1.16	0.31- 0.95	0.36- 1.00
MgO	14.21-23.36	9.55-31.81	9.97-28.03	9.06-29.63	8.35-30.32
CaO	1.08-22.65	0.27-21.45	0.57-19.64	0.21-19.25	0.46-11.76

Table 6.18. Ranges present in the troilites analyzed in Malvern and Molteno

	MALVERN	MOLTENO
Fe	57.65-64.01	62.02-62.76
S	30.21-36.65	35.85-37.34

Table 6.19. Ranges present in the glasses analyzed in Bununu, Malvern, and Molteno

	BUNUNU	MALVERN	MOLTENO
SiO ₂	47.50-51.07	42.05-54.69	44.91-74.12
TiO ₂	0.43- 0.73	0.19- 1.46	0.15- 4.37
Al ₂ O ₃	7.95-12.48	3.19-19.37	0.16-19.42
Cr ₂ O ₃	0.36- 0.83	0.11- 0.94	0.05- 1.13
FeO*	17.11-19.36	11.42-29.14	4.77-20.77
MnO	0.45- 0.51	0.28- 0.68	0.03- 0.58
MgO	9.82-16.29	3.51-17.37	0.81-18.93
CaO	6.31-10.08	0.27-11.51	4.68-12.34
Na ₂ O	0.14- 0.39	0.05- 0.80	0.00- 0.94
K ₂ O	0.02- 0.14	0.02- 1.50	0.00- 0.73

Table 6.20. Ranges present in the glassy microbreccias and devitrified glasses analyzed in Binda, Bununu, Malvern, and Molteno

	BINDA	BUNUNU	MALVERN	MOLTENO
SiO ₂	49.09-51.08	47.29-56.95	35.96-60.05	43.49-62.04
TiO ₂	0.10- 0.42	0.17- 0.65	0.20- 1.61	0.04- 1.61
Al ₂ O ₃	6.18-15.27	9.59-18.16	1.73-21.34	1.06-30.89
Cr ₂ O ₃	0.10- 0.38	0.08- 0.59	0.07- 0.67	0.06- 0.73
FeO*	14.02-18.82	13.62-19.23	12.40-21.73	5.29-19.67
MnO	0.31- 0.50	0.30- 0.50	0.27- 0.54	0.05- 0.53
MgO	12.93-19.48	4.31-14.12	2.50-14.90	2.13-15.04
CaO	3.75- 8.48	7.33-12.97	6.19-13.09	7.00-16.96
Na ₂ O	0.10- 0.33	0.13- 0.78	0.08- 1.07	0.00- 1.16
K ₂ O	0.00- 0.02	0.01- 0.07	0.02- 0.25	0.00- 0.12

Table 6.21. A comparison of the ranges, in cation %, of the main normative minerals of the glasses that occur in the howardites Bununu, Malvern, and Molteno (data from Appendix 3)

	BUNUNU	MALVERN	MOLTENO
Qz	0.00- 0.15	0.00- 1.92	0.00- 6.11
Or	0.12- 0.83	0.42- 9.07	0.12- 4.41
Pl	21.98-35.78	1.83-56.53	25.48-56.83
(Ab)	1.26- 3.60	0.46- 7.52	0.92- 8.74
(An)	20.72-33.49	1.37-49.73	21.42-51.42
Di	8.55-14.74	0.00-18.82	4.58-18.71
(Wo)	4.28- 7.37	0.00- 9.41	2.29- 9.35
(En)	2.71- 3.55	0.00- 4.70	1.33- 4.11
(Fs)	1.57- 3.83	0.00- 5.05	0.66- 5.31
Hy	42.05-66.97	25.66-64.73	28.61-63.70
(En)	20.23-42.42	17.62-36.97	12.11-40.16
(Fs)	20.72-24.55	13.57-30.46	15.58-27.10
Ol	0.00- 6.74	0.00-24.94	0.00-14.99
(Fo)	0.00- 3.65	0.00-12.84	0.00-10.02
(Fa)	0.00- 3.46	0.00-12.10	0.00- 4.97

Note: In order to make these ranges more meaningful, certain values from analyses with low totals, whose inclusion would have distorted the ranges, have been omitted. Similarly, a few highly anomalous compositions, e.g. MAGF1/21 and MOCF4/01, have been excluded.

Table 6.22. A comparison of the ranges, in cation %, of the main normative minerals of the glassy microbreccias and devitrified glasses that occur in the achondrites Binda, Bununu, Malvern, and Molteno (data from Appendix 3)

	BINDA	BUNUNU	MALVERN	MOLTENO	MALVERN devitrified glasses
Qz	---	0.00-17.58	0.00- 9.18	0.00- 9.02	0.00- 7.30
Or	0.00- 0.12	0.06- 0.41	0.12- 1.53	0.00- 0.74	0.12- 0.49
Pl	17.38-42.24	27.95-54.44	26.08-59.17	26.47-61.70	38.79-61.14
(Ab)	0.89- 2.94	1.18- 7.01	1.02- 8.44	0.00-10.89	3.80- 9.77
(An)	16.39-40.90	25.46-47.85	19.55-51.22	23.97-52.93	30.28-56.33
Di	0.69-5.46	8.06-23.50	4.75-19.45	5.87-22.12	3.70-14.39
(Wo)	0.34- 2.73	4.03-11.75	2.38- 9.73	2.94-11.06	1.85- 7.19
(En)	0.21- 1.77	1.67- 6.62	1.42- 3.81	1.46- 5.28	0.91- 3.80
(Fs)	0.13- 0.95	1.94- 6.97	0.95- 6.66	0.98- 6.87	0.94- 4.18
Hy	49.04-73.61	28.69-56.65	21.56-55.45	20.02-60.88	28.61-42.46
(En)	31.29-47.48	10.37-32.58	5.51-31.28	4.85-35.69	11.38-22.26
(Fs)	17.76-26.13	13.54-25.55	15.92-25.81	14.52-27.21	14.64-25.61
Ol	2.67- 8.13	0.00- 7.14	0.00-18.64	0.00-11.99	0.00- 9.50
(Fo)	1.64- 5.29	0.00- 4.01	0.00- 9.71	0.00- 7.99	0.00- 4.99
(Fa)	1.03- 2.91	0.00- 3.46	0.00- 8.93	0.00- 4.00	0.00- 4.52

Note: Two glassy microbreccias in Molteno (MOMBR2/08 and MOMBR2/10) were excluded from consideration because of their anomalous compositions, which would have seriously distorted the ranges.

6.6 DISCUSSION

Full discussion of the interpretation of the analytical data accumulated from microprobe investigation of the five brecciated meteorites is contained in the following chapter. However, some consideration of features of the tabulated chemical and normative data is appropriate at this point. Discussion of the chemical data centres on the ranges of composition observed in the various phases present in the meteorites studied. The normative data for the glassy phases are considered also in relation to the bulk norms of the host meteorites.

6.6.1 The non-opaque minerals

Pyroxenes

In Table 6.17, the data for orthopyroxenes and clinopyroxenes in Malvern are combined so that direct comparison may be made between all five meteorites. Two features emerge from study of the compositional ranges in this table: (i) a close similarity exists between Bununu, Frankfort, Malvern, and Molteno, and (ii) the ranges in Binda are more restricted than those of the other four achondrites and, with the exception of FeO*, lie entirely within the ranges noted in these meteorites. Furthermore, Malvern shows slightly greater variability in SiO₂, Al₂O₃, FeO*, and MnO than do the other three howardites in the main group.

Plagioclases

A situation parallel to that described above exists also in the compositional ranges of the plagioclases (Table 6.16), but is even more marked because the Binda feldspars show very little variation. Their compositions do, however, fall within the limits defined by the other four achondrites. In this mineral species, Malvern does not exhibit a wider spread of oxide values than those of Bununu, Frankfort, and Molteno.

Olivines

Little can be deduced from a comparison of the concentration ranges in olivines in Malvern and Molteno (Table 6.15) because the Malvern range is derived from a number of widely scattered clasts, whereas that of Molteno arises from small differences in the analyses of several crystals, all of which occur in the same dunite fragment and are presumably equilibrated. It should, however, be noted that the Malvern olivines show a fairly wide range of MgO values, and that the restricted compositions in Molteno are even more magnesian.

6.6.2 The opaque minerals

Chromites

The compositional ranges in the chromites of Bununu, Frankfort, Malvern, and Molteno are fairly wide and show a general similarity to one another, although those of Frankfort are more restricted than the others of this group (Table 6.12). Even narrower, however, are the ranges in Binda. As noted above for pyroxenes and plagioclases, the Binda analyses fall (with a few exceptions) within the ranges exhibited by the other four meteorites.

Ilmenites

Ilmenites were analyzed in Binda, Bununu, Malvern, and Molteno (Table 6.13). They show less compositional variability than the chromites. The widest ranges occur in Malvern, while the ilmenites in Binda show virtually a single composition within the limits of analytical variability. These observations may, however, result from the largest sample of ilmenites having been analyzed in Malvern, whereas Binda contains few examples of the mineral (Table 1.2). The compositions of Binda ilmenites generally fall within the ranges of the mineral in Malvern but not within those of the Bununu and Molteno ilmenites; e.g. MgO and Cr_2O_3 tend to be higher in the

Binda samples, and TiO_2 lower, than in those from Bununu and Molteno.

Troilites

Fe and S show more variation in the troilites in Malvern than in those of Molteno (Table 6.18). That this difference is real rather than apparent may be confirmed, despite the poorer quality of the Malvern analyses in this instance, by reference to Tables A3.31 and A3.32.

Metals

The overall compositional ranges in the metals of Bununu, Malvern, and Molteno are wide as a result of the presence of both kamacite and taenite (Table 6.14). Fe and Ni in the Bununu phase show a slightly smaller spread than in the metals of the other two howardites. The single analysis of metal from Binda (Table 6.3) differs markedly from all the other compositions observed in Bununu, Malvern, and Molteno. In particular, the content of Co (10.13%) is worthy of note.

6.6.3 The glassy phases

Glasses

Table 6.19 summarizes the compositional variability of glassy clasts in Bununu, Malvern, and Molteno. Considerable variation is present in most of the oxides listed. The ranges in the Molteno analyses are the greatest because of the presence of some clasts of fairly acidic composition, the resultant raising of the upper limit of the SiO_2 range being accompanied by lowering of the lower limits of FeO, MnO, and MgO. Bununu, which possesses the most uniform-looking glasses, exhibits the least variation. With the exception of the values for TiO_2 , FeO, and MnO, the bulk analysis of Bununu lies within the compositional range defined by its glasses (Table 4.10). The bulk analyses of Malvern and Molteno are wholly included in the ranges of their constituent glasses (Table 4.2).

Glassy microbreccias and devitrified glasses

These are again considered together in this section. As in the 'true' glasses, acidic materials extend the compositional ranges for Malvern and Molteno. Bununu has narrower ranges, and the limited number of clasts of this type in Binda show even more restricted variability (Table 6.20). The single analysis available from Frankfort lies within the Binda compositional limits except for Cr_2O_3 and the alkalis. The bulk analyses of Malvern and Molteno (Table 4.2) lie wholly within the ranges set out in Table 6.20, but the bulk analysis of Binda has higher Cr_2O_3 and MnO than is contained in the meteorite's glassy microbreccias. For Bununu, the match is poorer still; TiO_2 , Al_2O_3 , and CaO values are lower in the bulk analysis, and MnO and MgO higher, than in the glassy materials considered. The correspondence between the bulk analysis of Frankfort (Table 4.8) and the composition of that meteorite's solitary microbreccia clast is not close; major differences are present between the contents of Al_2O_3 , Cr_2O_3 , MgO, and CaO.

6.6.4 The normative data

Glasses

The ranges, expressed in cation %, observed in the main normative minerals calculated for the glasses analyzed in Bununu, Malvern, and Molteno, are compared in Table 6.21. With the exception of normative quartz, which shows the greatest spread of values in the Molteno glasses, Malvern exhibits the most variability. The ranges present in the normative mineralogy of Bununu glasses are considerably narrower than those of the other two howardites, as might be expected from the relative uniformity of their chemical compositions (Table 6.19).

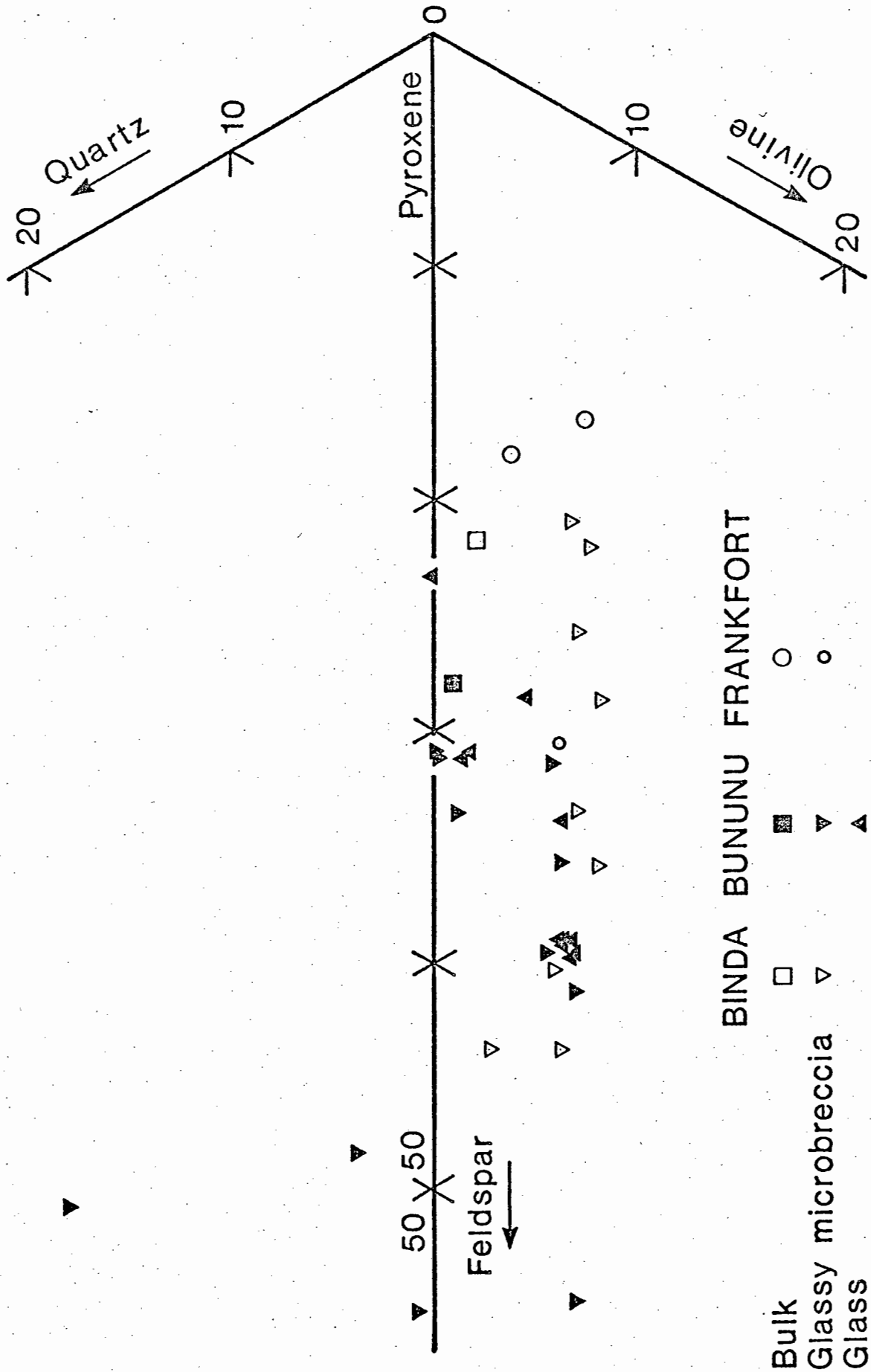
The normative mineralogical compositions of the glasses in Bununu, Malvern, and Molteno are graphically represented in the double ternary plots

(quartz - feldspar - pyroxene - olivine) of Figs 6.1, 6.2, and 6.3 respectively. Also shown are the norms of the bulk meteorites, taken from Fig. 4.1. Fig. 6.1 reveals that all the Bununu glasses lie in the olivine-normative field of the plot, that they are disposed in an elongate field that includes the bulk norm and trends slightly away from it towards olivine, and that all but one of them lie on the feldspar side of the bulk norm. A somewhat similar situation may be seen in the normative plot of the Malvern glasses (Fig. 6.2), but a few of the compositions plot in the quartz-normative field and three of the main cluster of points fall on the pyroxene side of the bulk norms. In Fig. 6.3 the norms of the Molteno glasses are distributed more or less along the feldspar-pyroxene join, with all the points falling nearer to the feldspar apex than does the norm of the bulk meteorite. This displacement of the norms of the glasses is therefore common to all howardites, and will be discussed further in the following chapter.

Glassy microbreccias and devitrified glasses

The extent to which the normative mineralogy of the glassy microbreccias and devitrified glasses in Binda, Bununu, Malvern, and Molteno varies is summarized in Table 6.22. The figures do not reveal any clear pattern, but the greatest ranges tend to occur in the mineralogy of Malvern or Molteno, and the least in that of Binda. The Malvern devitrified glasses are considered separately (Table 6.22), but their incorporation into the main body of data on Malvern would merely extend the ranges of plagioclase and diopside slightly, without basically altering the situation noted above. The ranges in normative mineralogy of the glassy microbreccias in Bununu and Molteno tend to be wider than those for the corresponding glasses, but the reverse is true for Malvern, in which only the range of normative quartz is greater for the glassy microbreccias than for the glasses. The norm of the single glassy microbreccia observed in Frankfort (Table 6.11) lies within

Fig. 6.1. Normative mineralogical compositions of glassy materials in Binda, Bununu, and Frankfort plotted in the double ternary diagram quartz - feldspar - pyroxene - olivine in cation %. Norms of the bulk meteorites (see Chap. 4) are plotted for comparison. Almost all the points fall in the olivine-normative field, and they do not cluster around their respective bulk norms. Instead, they define elongate fields that trend towards the feldspar apex. Bununu 'true' glasses are slightly enriched in the olivine component also, whereas the glassy microbreccias tend to be more quartz-rich and show greater variability than the glasses. The single glassy microbreccia in Frankfort is far removed from the bulk norms of both Frankfort (F) and Frankfort (T).



BINDA BUNUNU FRANKFORT

Bulk

Glassy microbreccia

Glass

Fig. 6.2. Normative plot of clasts of 'true' glass in Malvern, with the norms of the four bulk analyses used throughout the investigation included for comparison. As noted in the previous figure, most of the analyses plot in the olivine-normative field and trend away from the positions of the bulk norms towards richness in the feldspar component and, to a lesser degree, in olivine. There is no evidence for clustering around the bulk compositions.

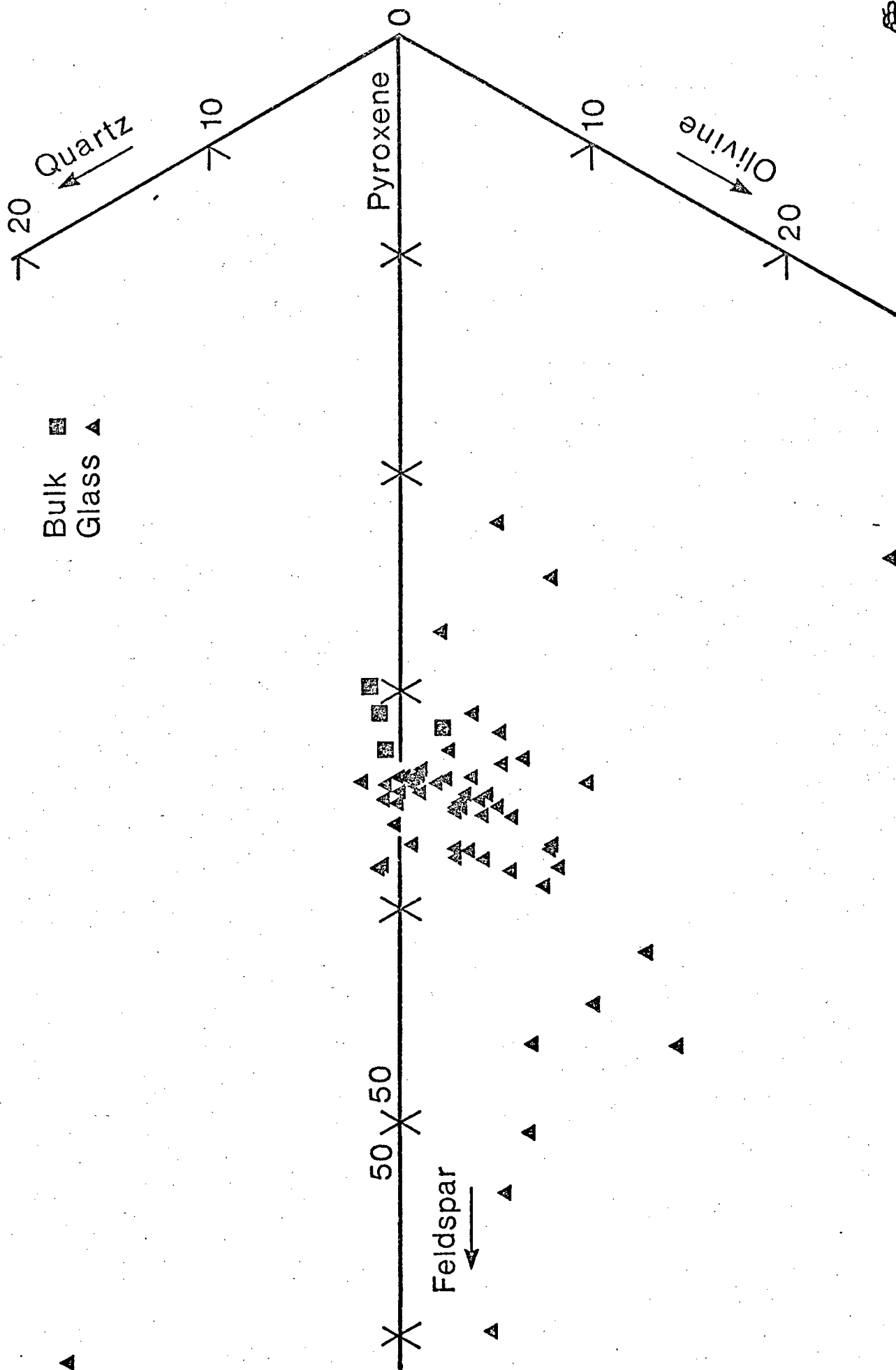


Fig. 6.3. Normative plot of the 'true' glasses in Molteno; cf. the two preceding figures. In this instance, the analyses lie along the boundary between olivine- and quartz-normative fields. As previously noted, they trend towards the feldspar apex and away from the norm of the bulk meteorite which, significantly, plots at the pyroxene extremity of the trend. The distribution of points in this figure shows a slight tendency towards quartz enrichment as opposed to the olivine enrichment of Bununu and Malvern glasses.

AB

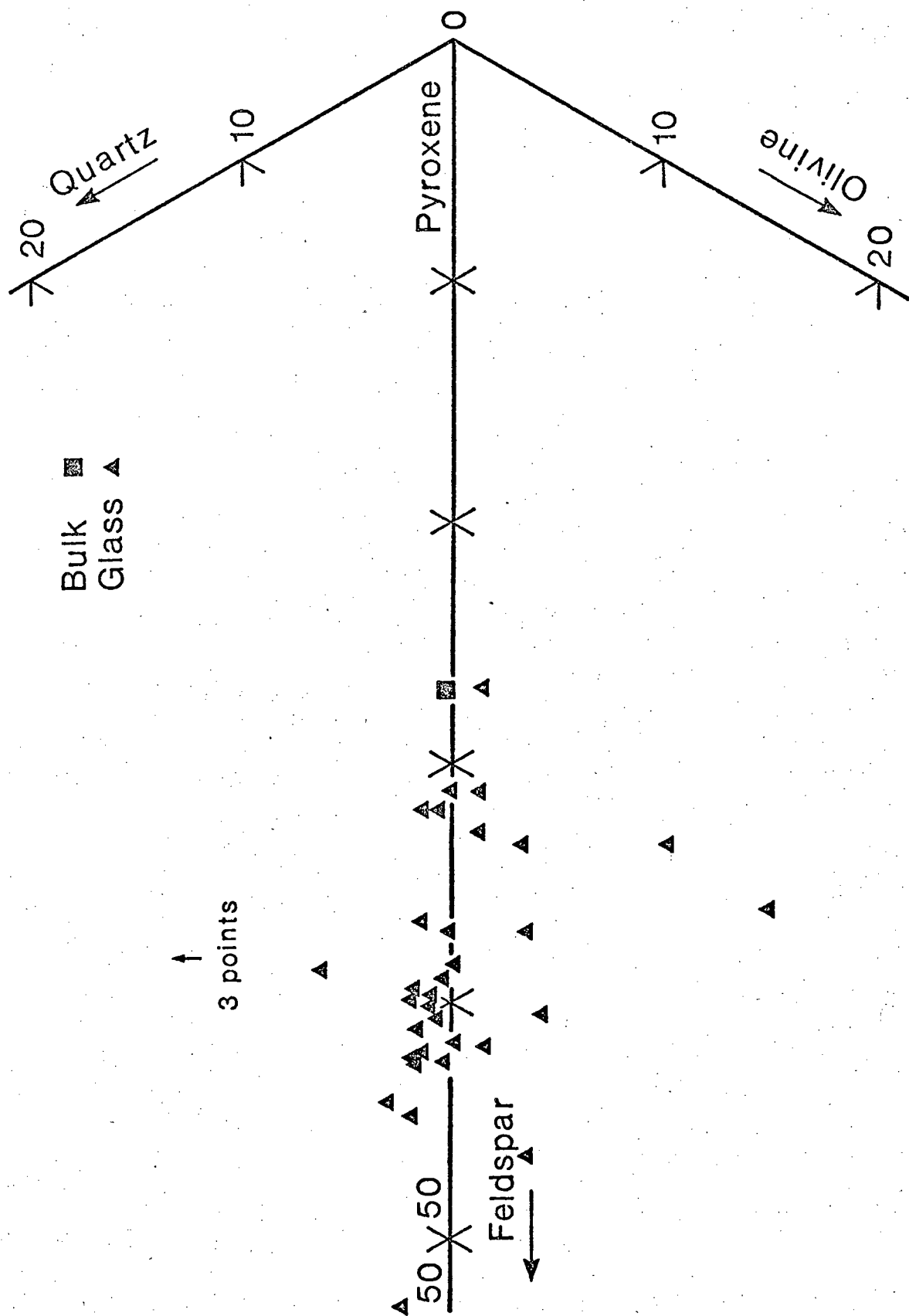


Fig. 6.4. Points representing the normative compositions of the matrix materials in glassy microbreccias in Malven define an irregular field whose elongation is controlled by enrichment in feldspar and olivine components. The bulk norms of the meteorite plot at one extremity, presumably the origin, of this trend. Only four points fall outside the main field, which lies completely within the olivine-normative half of the diagram.

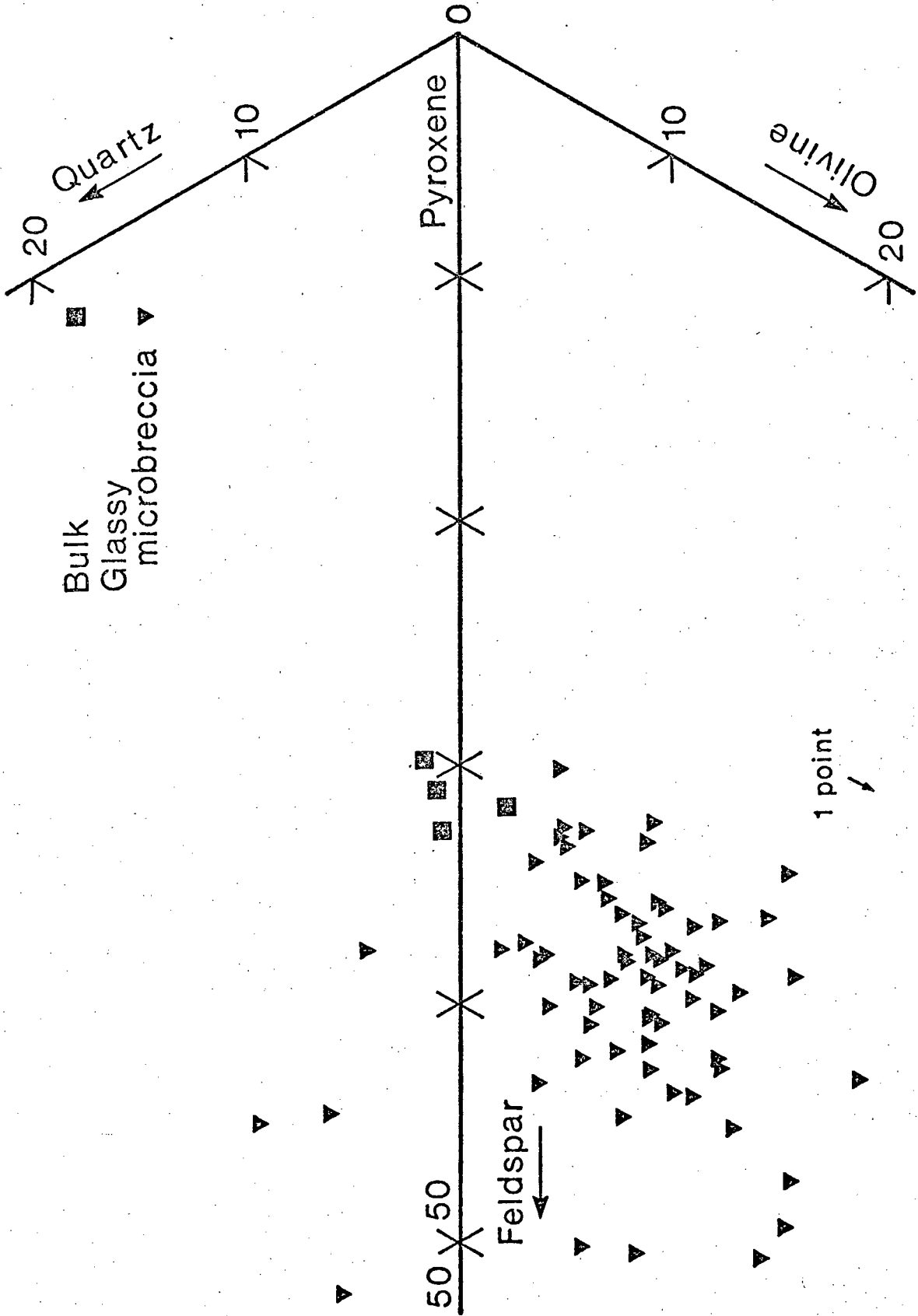


Fig. 6.5. The normative compositions of glassy microbreccias in Molteno show the same general characteristics as those of the glasses (Fig. 6.3) and plot along the boundary between quartz- and olivine-normative fields. All are enriched in the feldspar component relative to the norm of the bulk meteorite and, as previously noted, the bulk norm may be the origin of the trend.

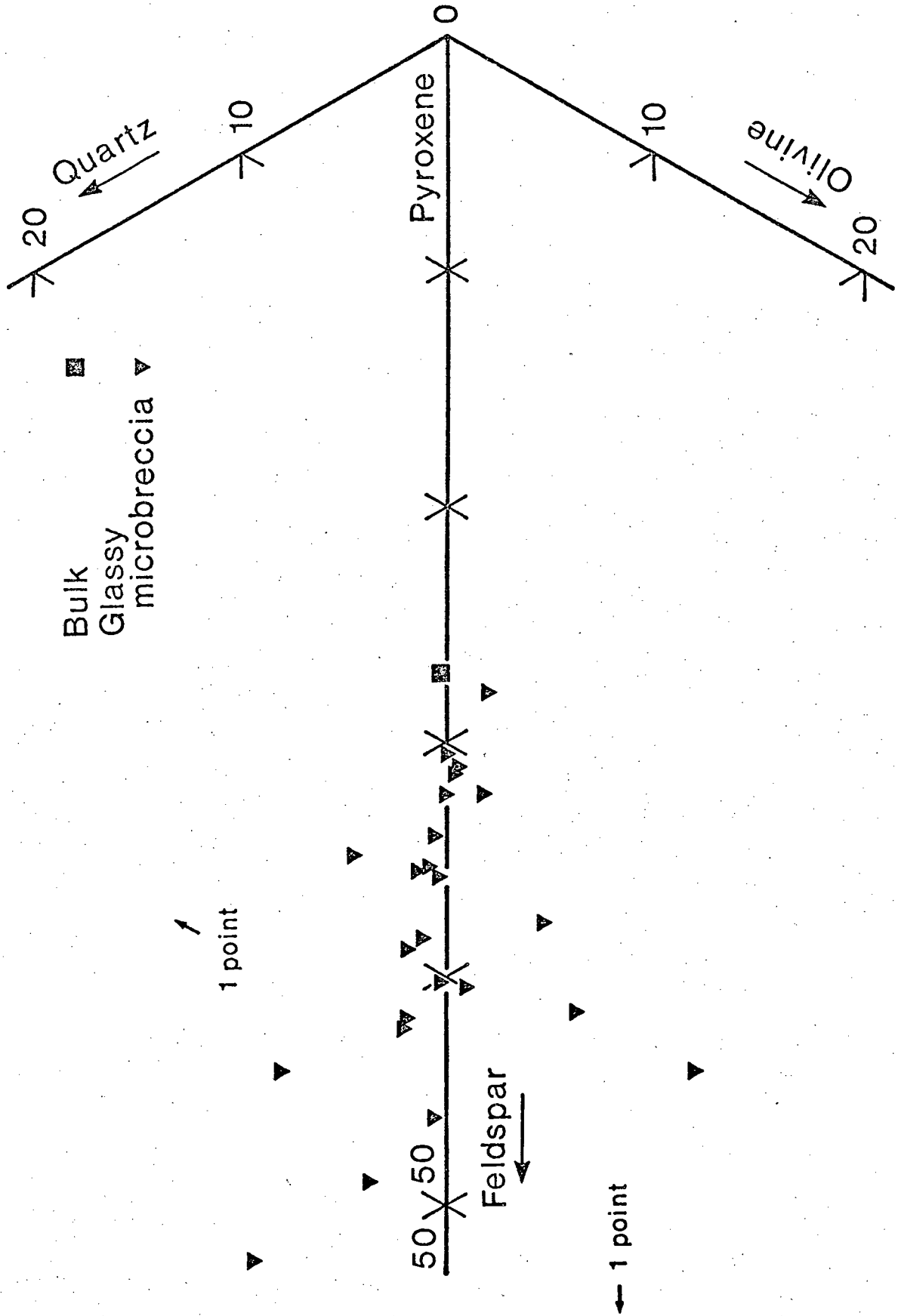
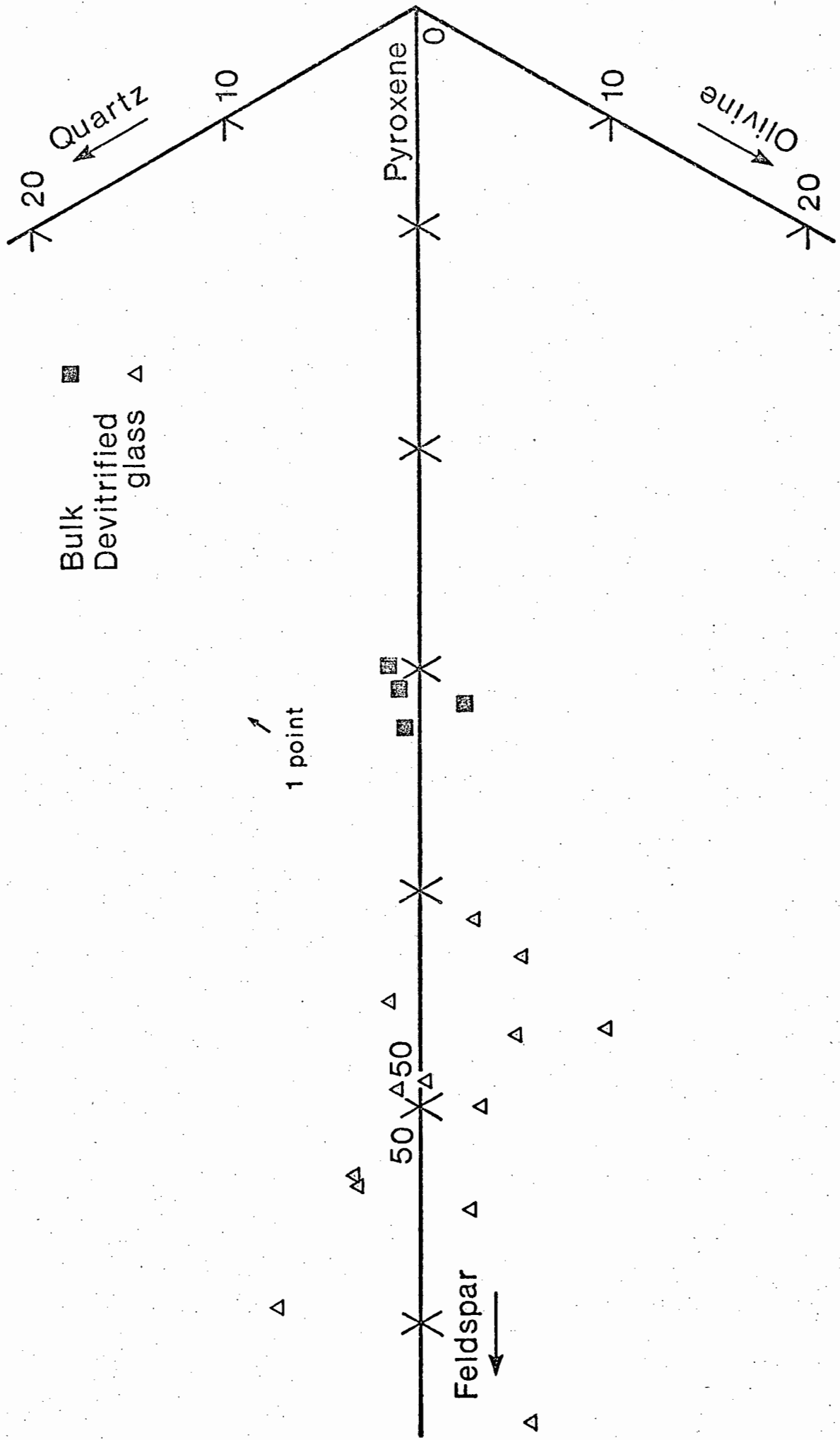


Fig. 6.6. Normative compositions of devitrified glasses in Malvern are irregularly distributed along the pyroxene-feldspar join. They show evidence of feldspar enrichment relative to the bulk norm of the meteorite, but not of olivine. They therefore resemble the glasses and glassy microbreccias of Molteno more strongly than those of the host meteorite. This fact, together with petrographic observations made (Chap. 3) on the glassy materials in Molteno, suggests that a tendency towards normative olivine enrichment is eradicated by devitrification, which is more evident in Molteno than in Malvern.



the ranges defined by the Bununu - Malvern - Molteno group of howardites; its content of normative orthoclase and diopside does not correspond with the ranges of these minerals in Binda (cf. the chemical comparison in section 6.6.3).

Plotting of the norms of the glassy microbreccias in the same way as was used for the glasses reveals certain similarities between these materials (Figs 6.1, 6.4, and 6.5). All the normative compositions plotted are richer in feldspar than is the corresponding host meteorite, and the elongate fields in which they lie are directed away from the position occupied by the host meteorite with a slight tendency towards olivine enrichment. This latter feature is very marked in the Malvern microbreccias (Fig. 6.4), but is almost absent from those of Molteno (Fig. 6.5; see also the plot of the Molteno glasses - Fig. 6.3) and from the Malvern devitrified glasses (Fig. 6.6). These observations, together with other compositional evidence discussed in the following chapter, have an important bearing on ideas currently held on the mode of formation of the glassy materials contained in some howardites (e.g. NOONAN, 1974; DESNOYERS and JÉROME, 1974; SIMPSON, 1974, 1975; DESNOYERS and JÉROME, 1977). The plotted normative data indicate that these glassy phases are not merely melts of the fragmental materials that make up the host meteorites in the correct proportions for producing the bulk compositions of the hosts. Selective fusion, particularly of feldspar, must have taken place during formation of the glassy materials contained in the five non-chondritic breccias studied. Furthermore, comparison of the compositional ranges in Figs 6.1 - 6.6 with that in Fig. 4.1 shows that total fusion of any composition in the eucrite series, as suggested by DESNOYERS and JÉROME (1974) for the origin of brown glass in Bununu, is incapable of producing the most feldspar-rich glasses present in these five meteorites.

CHAPTER 7

INTER-ELEMENT RELATIONSHIPS IN THE CONSTITUENT PHASES OF THE FIVE ACHONDRITES STUDIED

If you want to see worms,
you have to stare at the ground.

Snoopy (1952 ad infinitum)

7.1 INTRODUCTION

A major part of the study reported was devoted to microprobe analysis of the constituent phases of five achondritic, or non-chondritic, meteorites - Binda, Bununu, Frankfort, Malvern, and Molteno. The compositional data gained has been presented in part in the preceding chapter, and in full on the appended microfiche cards. This chapter deals with the interpretation of these data in the averaged form found in Appendix 3. Because of the volume of information involved, a graphical approach has been employed wherever possible.

Apart from the obvious purpose of acquiring much-needed data on the phase chemistry of these meteorites, the analytical programme had certain definite aims. These were:

- (1) To establish the presence and extent of compositional ranges in the components of these meteoritic breccias, thereby determining the character of the brecciation.
- (2) To ascertain whether these compositional ranges are continuous or discontinuous and, using the pyroxenes, to test for the bimodality of distribution implicit in the two-component mixing hypothesis of JÉROME and GOLES (1971) proposed for the formation of the howardites.

- (3) To compare the compositions of the various glassy constituents with one another and with the bulk composition of the host meteorite in order to gain information on the mode of origin of these glasses.
- (4) To determine, from a study of the material included in the glassy constituents, whether re-equilibration has taken place as a result of post-formational heating of the clastic components of these breccias while resident in their formational environment at the surface of the parent body (or bodies).
- (5) To use the information gained from the micro-analytical programme, in conjunction with the petrographic and bulk chemical data already presented, to form as accurate an impression as possible of the conditions of formation of these brecciated meteorites that would be of value in the formulation of a hypothesis for the origin of the achondrites in general.

The sequence followed in this chapter is the same as in Chap. 3 - non-opaque phases followed by the opaques, with 'whole-rock' (glassy and devitrified glassy) materials considered last. Particulars of the numbers of analyses carried out on the various phases in the five meteorites are set out in Table 1.2.

No systematic method of selection of material for analysis (e.g. by means of a grid) was employed. Instead, care was taken to ensure a reasonably random selection of the more abundant phases throughout the sections studied. Less freedom of choice was available, of course, for the scarcer materials.

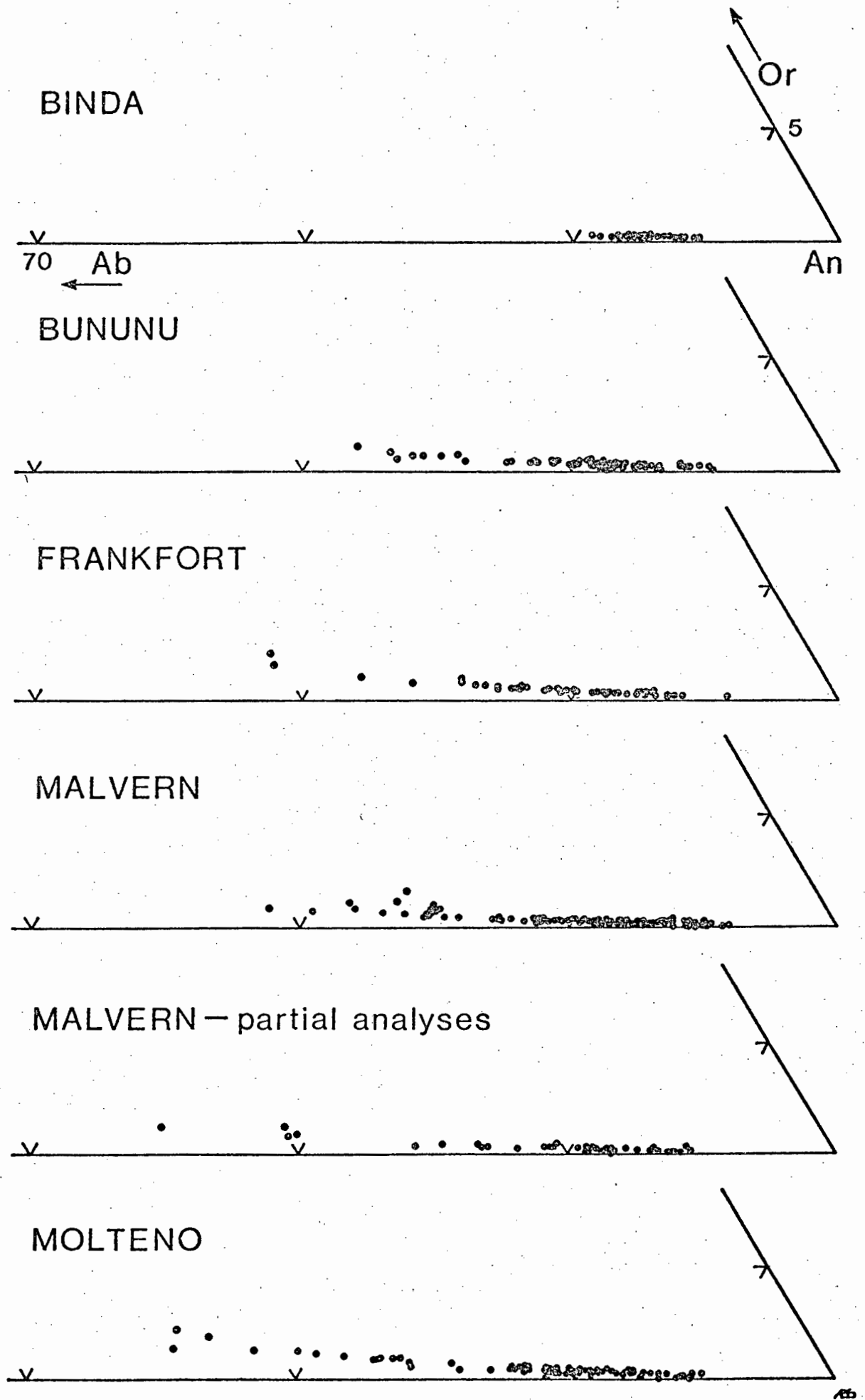
7.2 THE PHASE CHEMISTRY OF THE NON-OPAQUE MINERALS

7.2.1 Plagioclases

The plagioclase analyses produced in this investigation were interpreted mainly by means of plotting them, after appropriate recalculation, on the customary orthoclase-albite-anorthite ternary diagrams. Since all the plagioclases proved to be very Ca-rich, an enlargement of part of the ternary close to the An vertex was adequate for the plotting (Figs 7.1 - 7.3). Fig. 7.1 shows the distribution of all analyzed plagioclases for each of the five meteorites; the partial analyses of Malvern plagioclases are plotted separately from the complete analyses. The four meteorites whose classification as howardites is not in question - Bununu, Frankfort, Malvern, and Molteno - all display extended compositional ranges in their plagioclases. These lie within the approximate limits An_{75} to An_{96} , with the greatest concentration of analyses falling in the range An_{90} to An_{93} . Bununu shows the least extensive, Molteno the most extensive, of the ranges, but all are continuous if allowance is made for incompleteness of sampling. Binda, which has been shown by the petrographic part of this investigation (Chap. 3) to be essentially monomict and by the interpretation of its bulk composition (Chap. 5) to be howarditic or mesosideritic, but certainly not eucritic, displays a more limited range of plagioclase compositions (about An_{91} to An_{95}); GARCIA and PRINZ (1978) report an identical result. This range is, however, greater than might be expected from a truly monomict sample, and is not an artefact of analytical imprecision; it can be shown from the data of Table A8.2 that the total variation in the plotted position of an analysis on this diagram is about An_1 at the 95% confidence level, and is therefore insufficient to account for a range of An_4 .

The presence and extent of the compositional ranges in the plagioclases of the four howardites suggest that differentiation processes have

Fig. 7.1. Plagioclase compositions in Binda and the four howardites studied, expressed as mole percent and plotted in the Or-Ab-An ternary. All the plagioclases are relatively calcic, but within this limitation they show extensive and continuous compositional variation except for the Binda representatives. These display a restricted range of compositions (An_{91} to An_{95}) that is nevertheless wider than can be accounted for by analytical variation. In the four recognized howardites, the compositional ranges are similar to one another and suggest that the plagioclases have been derived from a series of source rocks related by igneous differentiation. The slightly narrower range recorded from Bununu is believed to be an expression of less complete sampling of the feldspars of the source region by that meteorite, or at least by that part of it that was studied.



operated on the source materials from which the feldspars were derived. The trends are regular, with the alkalis increasing regularly as Ca decreases. DUKE and SILVER (1967) state (p. 1659) that "plagioclase compositions are uniformly calcic in (howardites) and show no signs of differentiation", but this is at variance with their own observation (p. 1652) that the plagioclase compositional range in howardites is similar to that in eucrites, which they report as An_{80} to An_{95} . It appears most probable that the plagioclases in the four howardites studied originated in rocks of eucritic composition that were themselves differentiated. This is in accordance with the views of STOLPER (1977a) that the partial melting processes that generated the eucrites came to an end with the exhaustion of plagioclase from the source region, and that the more magnesian materials found in other achondrites and mesosiderites were produced from the plagioclase-depleted residues.

There is good agreement between the analyses plotted in Fig. 7.1 and normative plagioclase compositions calculated from the bulk chemical data. The normative compositions obtained from the data of Table 4.12 are An_{90} and An_{91} for the two Malvern samples, An_{93} for Binda, and An_{90} for Molteno, values that correspond with the densest part of the distribution in Fig. 7.1. The norms of Bununu and the two Frankfort analyses in Table 4.15 yield plagioclase compositions of An_{88} , An_{89} , and An_{84} respectively, which are slightly less close to the median values in the compositional ranges recorded.

Figs 7.2 and 7.3 present an analysis of how, in each meteorite, the analyzed plagioclases are distributed in terms of their mode of occurrence, i.e. as clasts in the 'matrix', as inclusions in glassy materials, or as components of lithic clasts of igneous or metamorphic appearance. They show also whether the analyzed feldspars occur in a single lithic clast, or are

included in a single glassy body. This information is of importance in determining whether or not re-equilibration has taken place.

The petrographic work reported in Chap. 3 showed Binda to be a special case, giving the impression of an igneous cumulate brecciated in situ. Almost all the material, therefore, is lithic, but a distinction is drawn in Fig. 7.2 between plagioclases that occur in the coarsely fragmental parts and those in the so-called 'matrix', i.e. the more finely cataclastic interstitial material. These 'matrix' plagioclases show the same compositional range as the others. They could not all be plotted, but the highest concentration of points falls between the arrows in the figure. There appears, therefore, to be no significant difference between the feldspars in the coarsely and finely crushed material in Binda.

The first of the two plots devoted to Bununu (Fig. 7.2) depicts the distribution of plagioclases that occur as separate mineral clasts, and comparison with the total distribution (Fig. 7.1) shows that the full compositional range is represented. The same is true of the crystals in lithic clasts, implying that differentiation operated in the production of the pyroxene-plagioclase rocks from which they were derived. These source rocks appear to have attained equilibrium, judging from the absence of zonation in the plagioclases and the compositional identity (within the limits of analytical precision) of crystals in the same clast. Feldspars included in several glassy bodies in Bununu do not show the full compositional range, but are restricted to its more calcic part. This may, however, be attributable to incomplete sampling. A similar explanation may apply to the range recorded in plagioclases in lithic clasts in Frankfort (Fig. 7.3), which is slightly less extensive than that of the mineral clasts.

A somewhat different situation is evident in Malvern (Fig. 7.3), in which the numerous mineral fragments are almost entirely in the range

Fig. 7.2. Distribution of plagioclases between different modes of occurrence in Binda, Bununu, and Molteno, for comparison with their total disposition (Fig. 7.1).

Binda: Because of the cataclastic nature of the brecciation, the only distinction drawn is between plagioclases in the larger fragments (solid circles) and those in the more finely comminuted 'matrix'. The figure shows their distributions to be identical. Not all the 'matrix' plagioclases could be plotted; their greatest density lies between the two arrows.

Bununu: (a) Plagioclases present as mineral clasts in the 'matrix' extend over the whole compositional range shown in Fig. 7.1. (b) Plagioclases that occur in lithic clasts have a spread of compositions identical to that of mineral clasts in the 'matrix'. Crystals in the same lithic fragment (outlined) are in equilibrium. Mineral clasts included in glassy microbreccias are concentrated in the more calcic part of the compositional spectrum, but this may be a result of the inavailability of a complete sample - glassy microbreccias are scarce in this howardite.

Molteno: (a) Plagioclase clasts in the 'matrix' of this howardite display the full compositional range, but less calcic members are sparsely represented. (b) The feldspars in lithic clasts are restricted to the calcic half of the range. Crystals in a large fragment (outlined) are roughly in equilibrium with one another. (c) Plagioclases caught up in glassy microbreccias show the compositional spread characteristic of the whole meteorite. The range of compositions present in a single glassy body (open circles) indicates that re-equilibration has not taken place.

BINDA

○ Clasts in the 'matrix'

Or

7 5



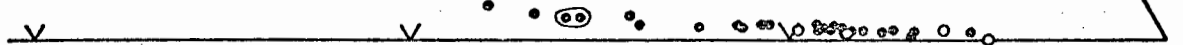
BUNUNU

a



b

○ In glassy microbreccias



MOLTENO

a

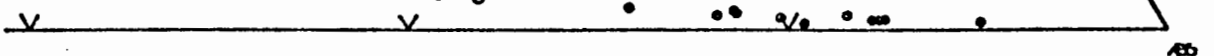


b



c

○ In a single glassy microbreccia clast



An₈₉ to An₉₆. The bulk of the compositions observed in lithic clasts also lie within these limits, but the total range is that of the full analyses in Fig. 7.1. As noted in Bununu, the plagioclases in these lithic fragments suggest equilibrium crystallization. Feldspars included in glassy materials show the full compositional range. Moreover, this range is represented by the inclusions in at least one of the glassy microbreccias studied, proving that no re-equilibration of such included material has taken place. The same phenomenon was noted in a clast of 'true' glass, the smaller range of compositions presumably reflecting merely the smaller number of included plagioclases available for analysis.

Fig. 7.3 includes data on the plagioclases in the large microbreccia clast (the "xenolith" of DESNOYERS and JÉROME, 1977). Plagioclases that form part of the equigranular 'matrix' of this clast exhibit a range about An₈₈ to An₉₄, roughly coincident with the densest part of the distribution observed in lithic clasts in the host meteorite. Three crystals from a pyroxene-plagioclase inclusion in the microbreccia are slightly more sodic. Their plotted positions show some scatter, but their alignment along the trend established for all the plagioclases in Malvern (Fig. 7.1) may indicate a slight lack of equilibrium rather than analytical error.

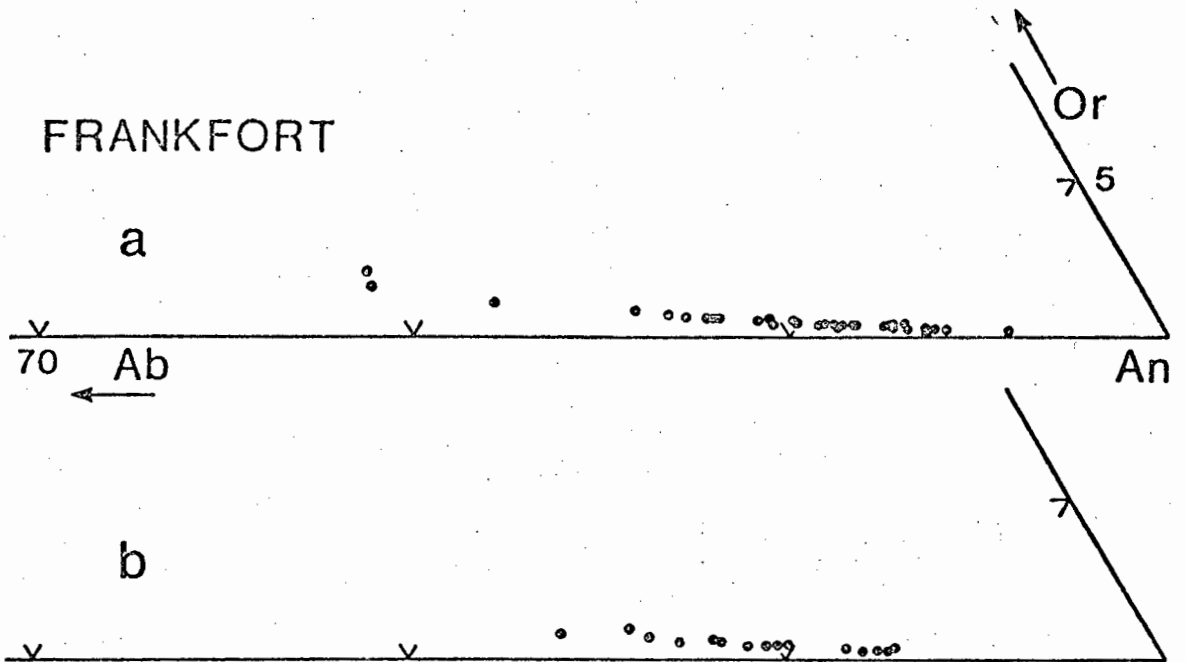
Mineral clasts in Molteno (Fig. 7.2) show a wide range of compositions, but the majority are concentrated in a much narrower spread identical to that of their Malvern counterparts. Plagioclases in lithic clasts in the meteorite display more compositional variety, again broadly similar to those from comparable material in Malvern. It is interesting to note that lithic clasts occur in both howardites in which the feldspars do not plot as closely as might be expected had they attained complete equilibrium, and that these feldspars have the same small range of compositions - approximately An₈₂ to An₈₄. To ascertain if this observation has any significance or is merely

Fig. 7.3. Distribution of plagioclases between different modes of occurrence in Frankfort and Malvern.

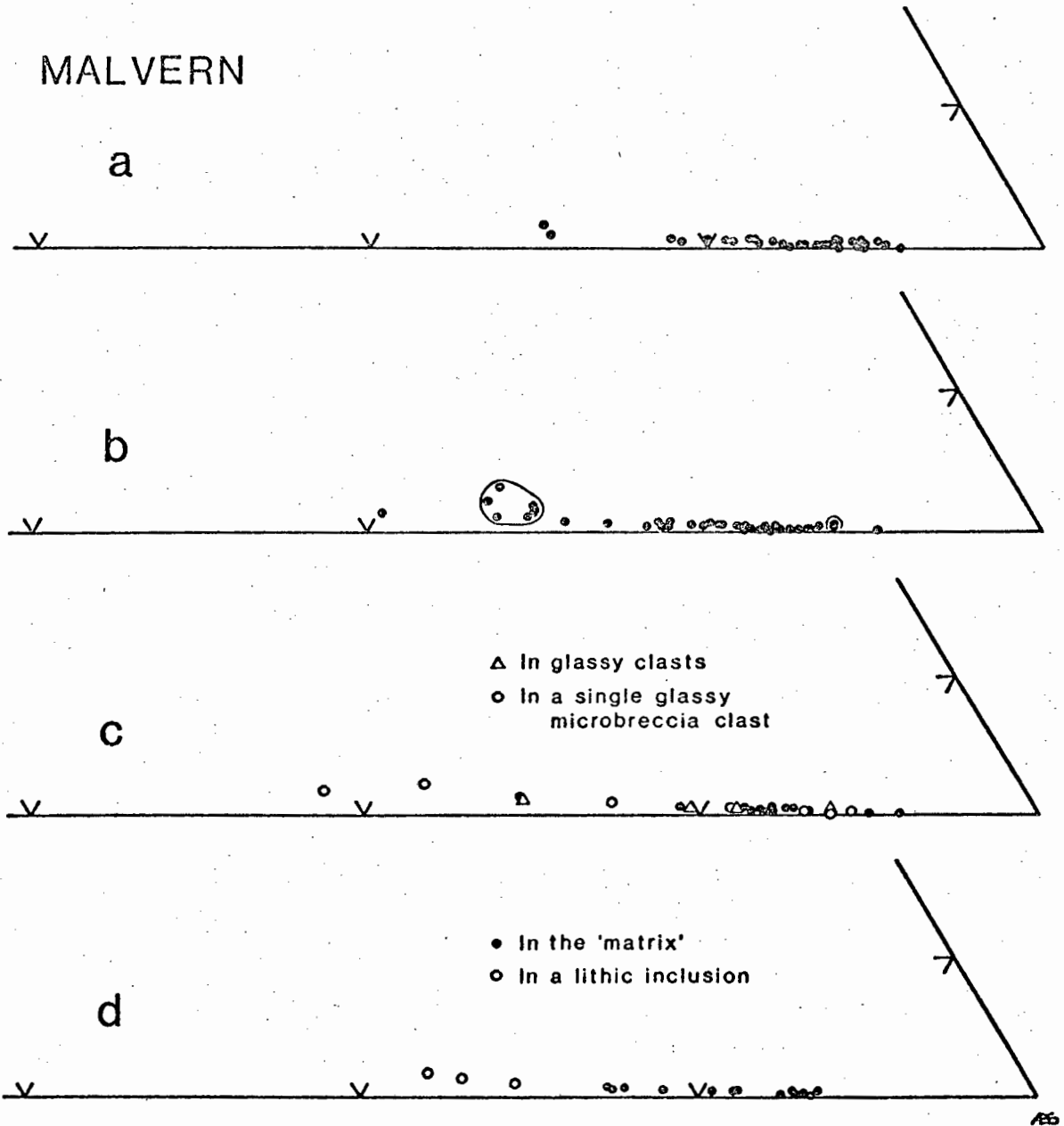
Frankfort: (a) Mineral clasts in the 'matrix' show the full compositional range seen in Fig. 7.1, with a bias towards the anorthitic end. (b) Plagioclases in lithic clasts occupy the same range as the majority of the mineral clasts in the meteorite; the more alkali-rich compositions are not represented.

Malvern: (a) The compositions of plagioclase clasts in the 'matrix' are largely restricted to the range An_{89} to An_{96} . (b) Plagioclases show a wider compositional spread and a shift away from the most calcic compositions where they occur in lithic clasts. Groups of analyses from the same fragment are outlined. Note that one group apparently displays better attainment of equilibrium than the other, but this may result from analytical factors. (c) The complete range of compositions is exhibited by plagioclases included in glassy microbreccias (circles) and in fact by those included in a single large glassy microbreccia body (open circles), showing that no re-equilibration took place. Plagioclase inclusions in 'true' glasses display a lesser range, probably because they are scarcer. (d) The plagioclases making up part of the equigranular matrix mosaic of the large microbreccia clast in Malvern have a more restricted compositional range than that of the host breccia, while those in a lithic inclusion in the microbreccia are richer in alkalis and apparently show a lack of equilibrium.

FRANKFORT



MALVERN



coincidental would require a more detailed study of the lithic clasts in howardites than was possible in the present investigation. The most extensive compositional range is shown by plagioclases included in the glassy microbreccias in Molteno. It is only slightly greater than that of the mineral clasts. As in Malvern, it was demonstrated that no re-equilibration of included plagioclases had occurred (Fig. 7.2).

The foregoing data suggest that the plagioclases found in howarditic breccias originated in source rocks that showed limited, but significant, differentiation involving these feldspars. The most probable sources of these plagioclases are the eucrites, which have been shown to be a differentiated series of limited extent by studies of their bulk chemistry (Chap. 5) and by computer modelling (Chap. 8). The petrographic studies of howarditic plagioclases in Chap. 3 showed that many of the lithic clasts are of eucritic appearance, but raised the problem that virtually none of the mineral clasts could have been derived from extrusive, or shallow intrusive, rocks with subophitic textures. Their crystal habit suggests origin in a cumulate, an impression strengthened even by some of the plagioclase-bearing lithic clasts. The literature on the mineral chemistry of the eucrites contains many gaps, some of which have been filled by the valuable work of MASON et al. (1979). Their data indicate a compositional range of An_{80} to An_{95} in the eucrites as a whole. This accords well with the range recorded in howarditic plagioclases in the present work, although the howarditic range extends farther in both directions. From the incomplete data available, it is clear that there are considerable variations between individual eucrites. The three cumulate eucrites are unbrecciated and equilibrated, as confirmed by their constant plagioclase compositions - Serra de Magé An_{95} (PRINZ et al., 1977) Moama An_{94} (LOVERING, 1975), and Moore County An_{91} (ISHII and TAKEDA, 1974). At the other end of the series, Lakangaon's plagioclases range between An_{81} and An_{90}

(MASON et al., 1979). Unfortunately data on Sioux County are lacking, but Juvinas and other 'main group' eucrites contain fairly wide ranges of plagioclase compositions that fall between the limits An_{80} and An_{93} (REID and DUKE, 1981). Béréba, however, shows little variation - An_{90} to An_{92} (MASON et al., 1979), a pointer to equilibration. The ranges quoted for the majority of the eucrites by Mason and his colleagues contradict the view of REID and BARNARD (1979) that most eucrites have been equilibrated by high temperature annealing.

Thus the plagioclases in the four howardites investigated reflect the compositional variations produced in the eucrites by crystal-liquid fractionation. The more alkali-rich varieties presumably had their origins in residual liquids such as Lakangaon and Nuevo Laredo (and perhaps even more Fe-rich eucrites not at present represented in meteorite collections). On the other hand, the tendency noted in the mineral clasts of all four howardites, whether in the 'matrix' or included in glassy materials, to be concentrated at the calcic end of the compositional range suggests derivation from eucritic cumulates, in part at least. This idea receives support from the petrographic observations of Chap. 3, but is difficult to reconcile with the complete absence of mixing lines (or possible igneous trends) connecting the howardites and cumulate eucrites in any of the inter-element plots considered in Chap. 5.

It must further be stressed that none of the variations recorded in the plagioclases of these howardites are attributable to zonation, which was detected neither optically nor chemically in any of the lithic or mineral clasts studied. The 'within-grain' type of variation reported from the unequilibrated eucrites (REID and BARNARD, 1979; REID and DUKE, 1981) was not found in this investigation, neither in the plagioclases nor in the pyroxenes. All variation occurs between clasts which, in the case of lithic materials, appear themselves to be in equilibrium.

7.2.2 Plagioclase stoichiometry

The lack of equilibrium in the source materials as a whole may, however, be assessed from a study of plagioclase stoichiometry. This technique was used by WEILL et al. (1970) to study the petrogenesis of some Apollo 11 igneous rocks. They found that the lunar plagioclases showed significant departure from stoichiometry compared to plagioclases from the Stillwater Complex (McCALLUM, 1968) that coincided with the theoretical values, and attributed this difference to the high rate of crystallization of the lunar lavas relative to the terrestrial layered intrusives. The plagioclase data from the present investigation have been recalculated to the atomic ratios and plotted as in Fig. 4b of the Weill paper, and are discussed below in the light of this finding and a later study of the crystallization of plagioclase in mare basalts (CRAWFORD, 1973). Crawford did not reach completely firm conclusions for the non-ideal behaviour of plagioclases in the lunar rocks investigated, but she appears to agree with Weill and his co-workers that the excess of Si and deficiency of Al resulted from rapid, non-equilibrium crystallization from a melt, and states (p. 714): "The deviation from ideality is absent near An_{100} and increases as the plagioclase becomes more sodic and more disordered."

Figs 7.4 - 7.7 show that the meteoritic plagioclases analyzed in this work also depart, in varying degrees, from true stoichiometric compositions and suggest that the concepts used in the lunar studies may be applicable to them. Binda and Bununu (Fig. 7.4), having the least extensive distributions, show the smallest degrees of deviation from the calculated line. All the Binda analyses plot within a small elongate area that is overlapped by many of the Bununu points. Together, the plagioclases of these meteorites make up a poorly-defined trend that traverses the calculated line at a low angle and, despite some scatter in the data for Bununu, presages the clear

trends of the other plots. A significant feature of this plot is that most of the Bununu analyses, and all of those from the Binda sample, fall on the opposite side of the calculated line from Apollo 11 plagioclases plotted by Weill and his colleagues, i.e. they have less Si and more Al for a given Ca than required by stoichiometry.

The plot of the plagioclases in Frankfort (Fig. 7.5) shows the same characteristics as noted for Binda and Bununu, but the trend is somewhat better developed and, if projected, intersects the abscissa of the plot at approximately the same position as do the lunar plagioclases of Weill's Fig. 4b. As in the previous diagram, however, the majority of the plagioclases analyzed in Frankfort show anomalously high Al/Al+Si (atomic) ratios as in Binda and Bununu. There is less scatter in the analyses of plagioclases in Frankfort than in their counterparts in Bununu.

The plagioclases in Malvern (Fig. 7.6) show the closest approach to the lunar situation encountered in the five non-chondritic meteorites studied. In this plot, very few of the analyses lie in the field of high Al/Al+Si ratios, and the remainder deviate from stoichiometry to form a linear trend similar to that of the lunar plagioclases, though not as extensive as that seen in the Apollo 11 examples (WEILL et al., 1970, Fig. 4b). The intercept on the horizontal axis would, as for Frankfort, be approximately the same as for the lunar feldspars.

The plot of the Molteno plagioclases shows a return to the sort of distribution seen in Bununu and Frankfort. In Molteno, however, the feldspars are more or less equally distributed between the two fields in the diagram, a situation intermediate between the plots of Frankfort and Malvern (Fig. 7.7). The trend noted in the previous plots is again apparent. The low angle at which it crosses the line of calculated stoichiometry in all of these plots means, of course, that a number of plagioclases are in fact stoichiometric,

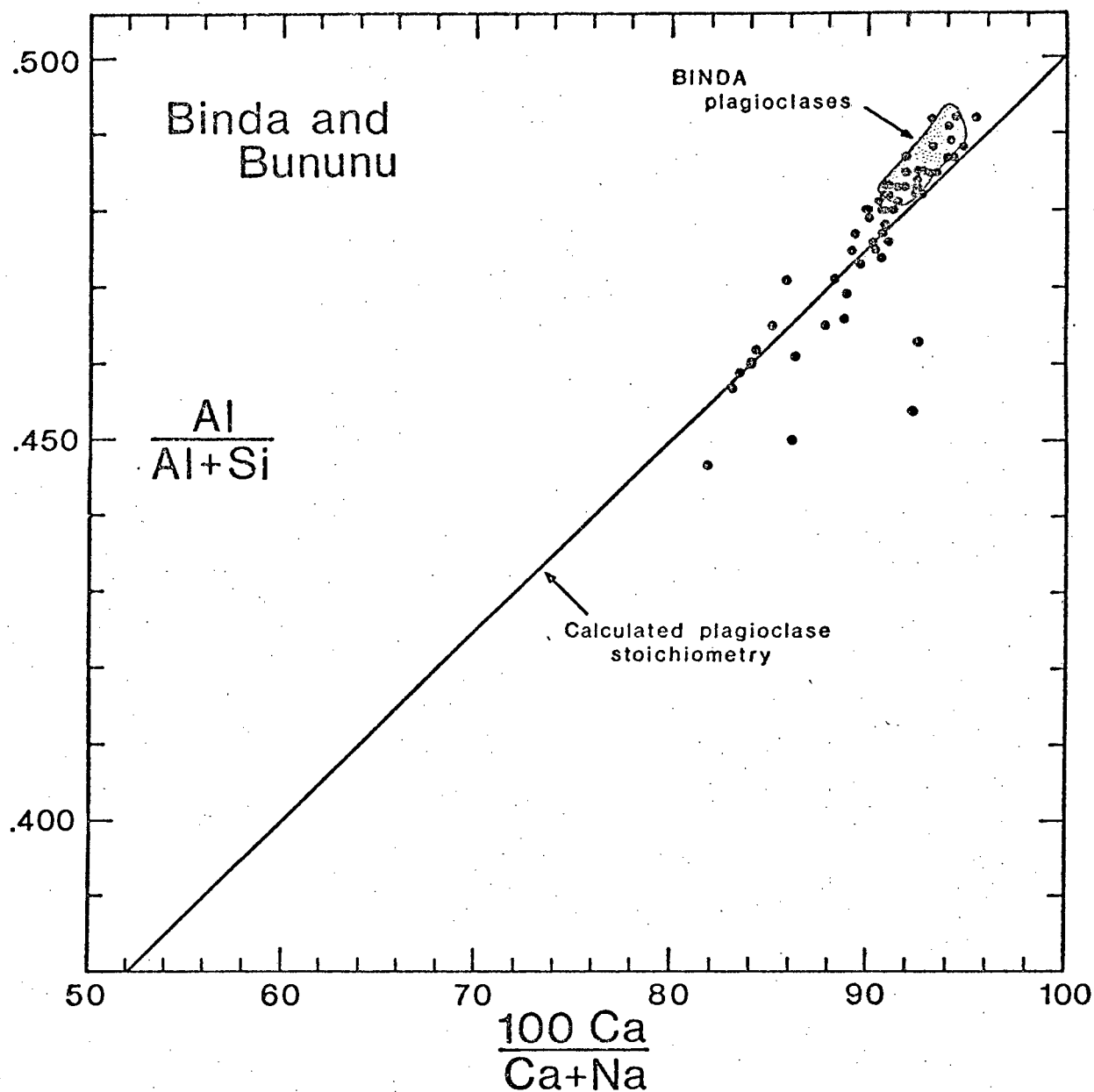


Fig. 7.4. Plagioclase stoichiometry in Binda and Bununu. In this and the succeeding three figures, the ratios on the axes are atomic. The solid line (calculated plagioclase stoichiometry) is taken from Fig. 4b of WEILL *et al.* (1970). The Binda plagioclases, too numerous to plot individually, lie in the stippled field. These, together with the bulk of the Bununu analyses, are non-stoichiometric but in the sense opposite to the Apollo 11 plagioclases studied by Weill and his colleagues. A roughly linear trend (better developed in the following plots) is evident in the plagioclases of these two meteorites.

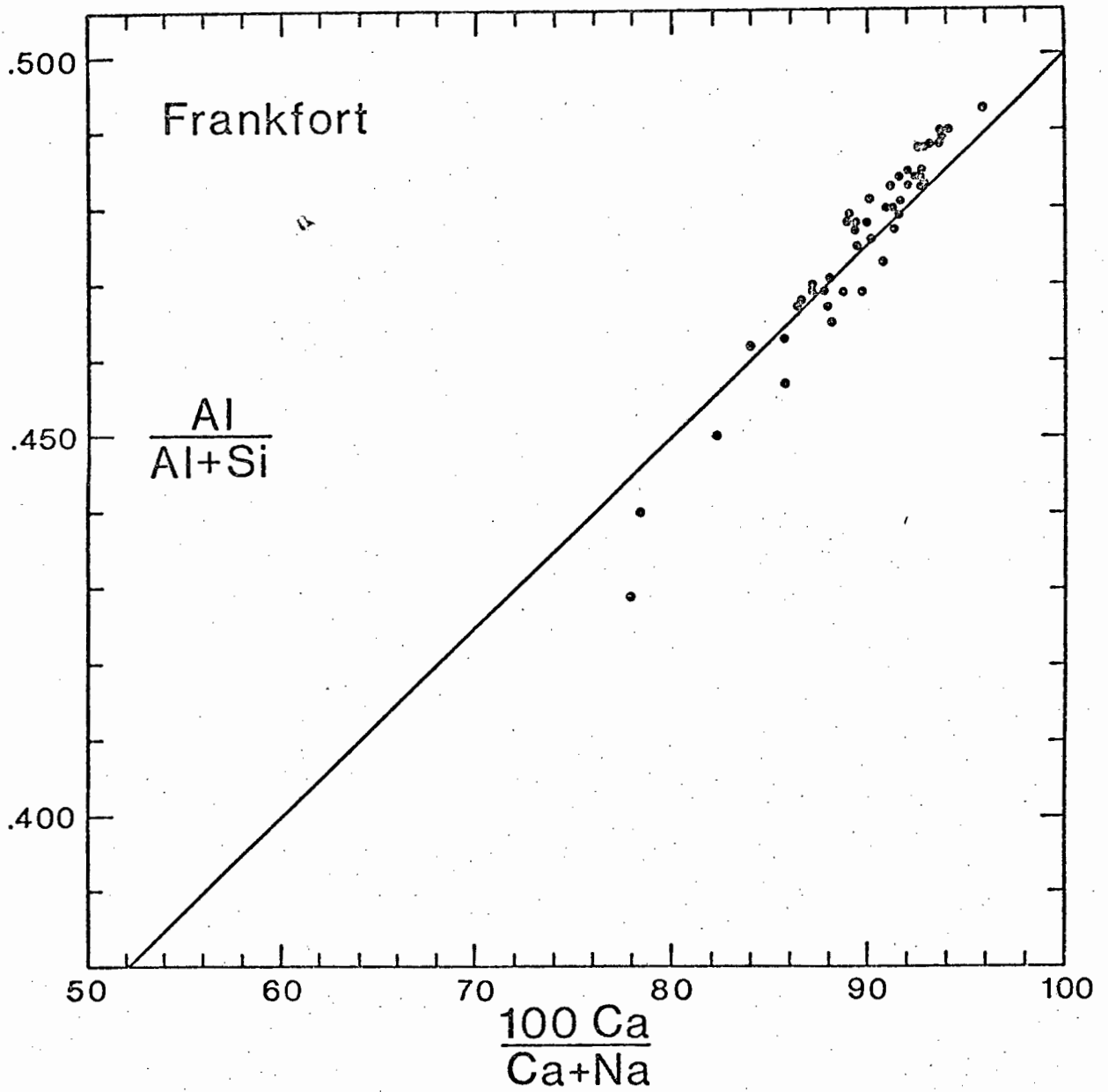


Fig. 7.5. Plagioclase stoichiometry in Frankfort. The distribution of the analyses is similar to that seen in Fig. 7.4, but the trend traversing the line of calculated plagioclase stoichiometry is more clearly developed. The projected intercept of this trend on the horizontal axis of the plot is closely similar to that of the lunar plagioclases but, unlike the lunar situation, the bulk of the analyses fall in the field of Al enrichment relative to Si.

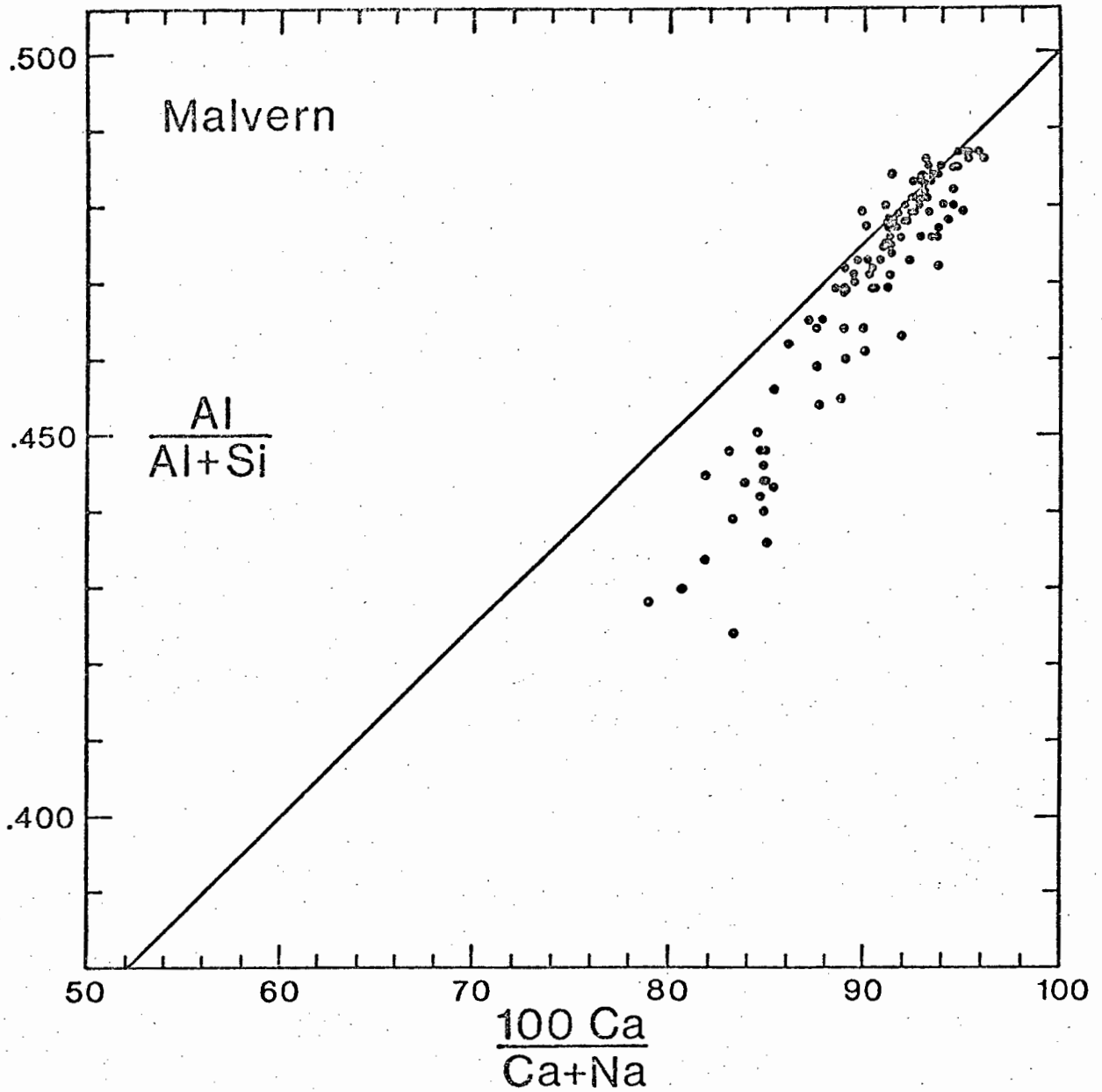


Fig. 7.6. Plagioclase stoichiometry in Malvern. A significant difference is apparent in this plot; very few of the analyses plot above the line of calculated stoichiometry. Consequently, the Malvern plagioclases show the closest resemblance to the Apollo 11 examples plotted by Weill and his co-workers, but the trends are not coincident. The Malvern trend, which is the most clearly developed in the howardites investigated, is intermediate between those of the other three howardites and the lunar plagioclase trend.

but this is judged of subordinate importance to their forming part of a trend that must have genetic significance.

The following conclusions can be drawn from Figs 7.4 - 7.7:

- (1) The great majority of the plagioclases in the five meteorites studied are not stoichiometric. The deviations, though for the most part not large, cannot be accounted for by analytical error (Table A8.2).
- (2) They define a trend similar in slope to that of the plagioclases in lunar igneous rocks but restricted in extent. The Binda plagioclases occupy a small field whose major axis follows the trend established by the feldspars in Bununu and Frankfort.
- (3) Unlike the lunar example, the trend does not originate at the line of calculated stoichiometry but at a point beyond it, in the part of the plot in which $Al/Al+Si$ ratios are higher than required by ideal compositions.
- (4) There is a slight but systematic shift in the position, but not the slope, of the trend lines from the Mg-rich host meteorites (Binda, Bununu, and Frankfort) through Molteno to Malvern and, at the end of the sequence, to the Apollo 11 igneous rocks studied by WEILL et al. (1970, Fig. 4b). This shift appears to be related to the composition of the rock that contains the plagioclases, but the reason for it is not clear.
- (5) In the field in which $Al/Al+Si$ ratios are lower than required by stoichiometry, meteoritic plagioclases deviate farther from ideal compositions as they become more sodic, in accordance with the observation of CRAWFORD (1973) on the plagioclases of mare basalts from a number of lunar sites.
- (6) As demonstrated by Figs 7.2 and 7.3, there are no simple and obvious divisions of the Ca/Na compositional spectrum, and therefore of the trends observed in the plots under consideration, into ranges

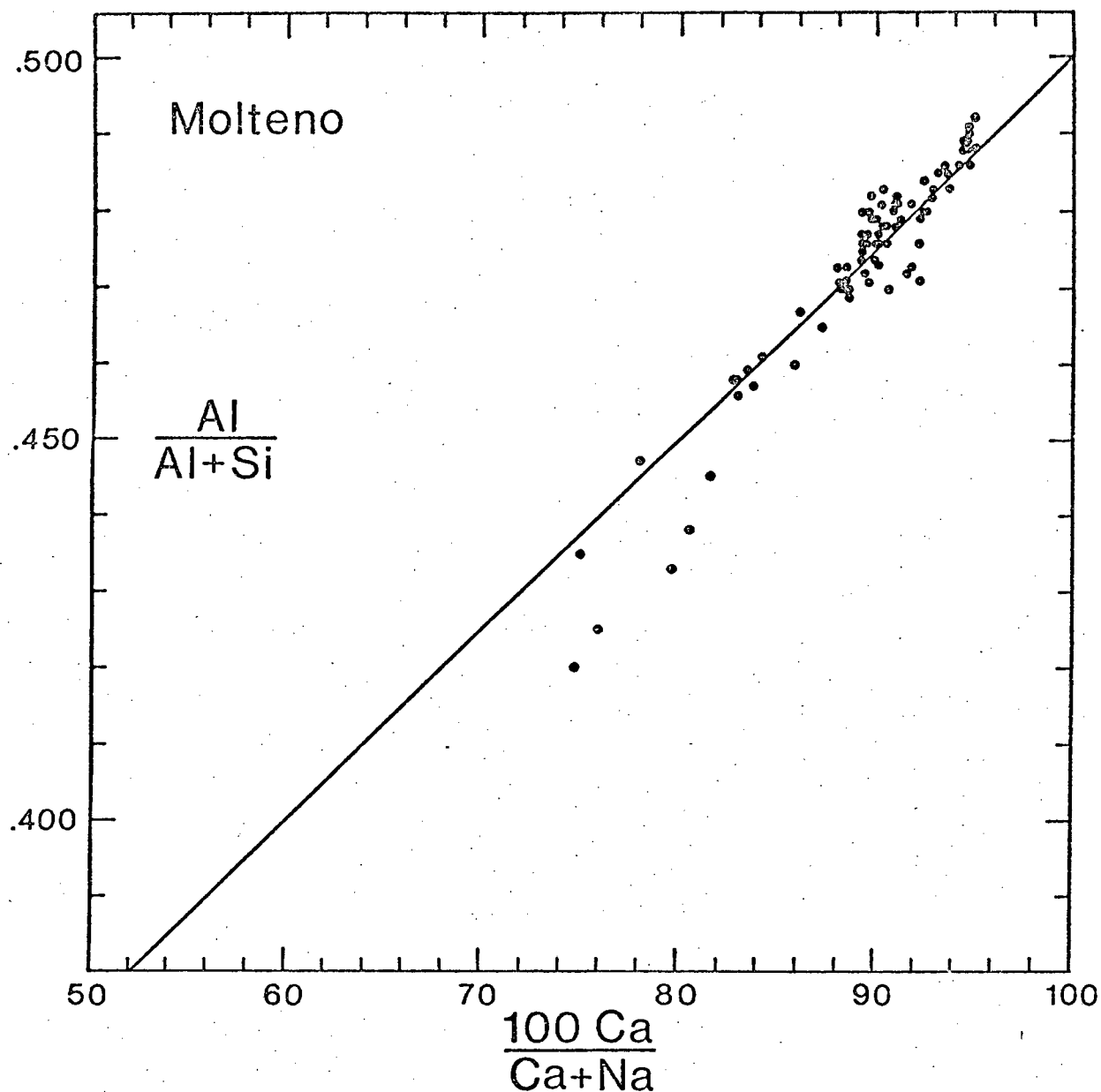


Fig. 7.7. Plagioclase stoichiometry in Molteno. The well-developed trend resembles that of Malvern in the preceding figure, but a significant proportion of the analyses plot above the line of calculated stoichiometry. The Molteno plagioclases therefore appear to be intermediate, in this system of plotting, between those of the most Mg-rich host meteorites - Binda, Bununu, and Frankfort - and Malvern, which is compositionally closest to the eucrites and lunar basalts.

attributable exclusively to plagioclases from rapidly-cooled lavas or to mineral clasts whose crystal habit suggests an origin under equilibrium conditions of slow cooling in cumulates that were subsequently disaggregated; essentially, plagioclases in all modes of occurrence cover the entire observed compositional spectrum. However, careful consideration of the data on the petrography of the lithic clasts and the compositions of their constituent plagioclases revealed that fragments with definite ophitic or sub-ophitic textures invariably contain equilibrated plagioclases that are relatively sodic (An_{85} or less), whereas those with definite cumulate textures have more calcic varieties (An_{90} or greater). Furthermore, the larger mineral clasts, i.e. those most likely to have originated in slowly-cooled cumulates, are also highly calcic. These observations therefore support the views of WEILL et al. (1970) and CRAWFORD (1973) on the connection between the cooling rates of extraterrestrial rocks and the stoichiometric state of their constituent plagioclases.

- (7) It can therefore be stated that, if the presumption that the plagioclases in howardites were derived from the eucrites is correct, then the eucrite series consists of a continuum of igneous rocks that have crystallized in a wide variety of cooling environments ranging from very fast to very slow, and the continuity of thermal relationships, as seen in the plots of plagioclase stoichiometry above, strongly suggests that these rocks are directly connected genetically.

7.2.3 Pyroxenes

A method similar to that employed for the plagioclases was used in the study and interpretation of the numerous pyroxene analyses available from this investigation. The approach was again largely graphical and involved

computer plotting of the analyses on the conventional pyroxene quadrilateral (diopside-enstatite-ferrosilite-hedenbergite) in molar proportions. The total data for each meteorite were first plotted, followed by separate plots according to modes of occurrence.

Binda

The pyroxenes analyzed in Binda are plotted in Fig. 7.8 and, like the plagioclases in that meteorite, show a very limited compositional spread - $Wo_{2.3}En_{65.5}Fs_{32.2}$ - $Wo_{2.7}En_{60.0}Fs_{37.3}$ for the Ca-poor varieties and practically no variation for the Ca-rich, the former being the orthopyroxene host phases resulting from the inversion of primary pigeonite, the latter the exsolved clinopyroxene phases (about $Wo_{45}En_{42}Fs_{13}$). Host-lamellae pairs are linked by tie-lines in the diagram, but not all could be shown. Because of the coarseness of the exsolution, no attempt was made to determine the bulk composition of the pyroxene crystals, i.e. the composition of the primary pigeonite, but this would present no great difficulty if a more modern microprobe were available. GARCIA and PRINZ (1978) reported a range of En_{62} - En_{67} for the host phase in their sample of Binda, i.e. very similar to that of the present study, and a bulk pigeonite composition of $Wo_7En_{62}Fs_{31}$, identical to that given by ISHII et al. (1976). The scatter of points at the Fe-rich end of the orthopyroxene range in Fig. 7.8 merely reflects the inability of the microprobe to resolve the exsolved clinopyroxene phase and is evident in many of the following figures also. In this instance, it suggests that the exsolution lamellae tend to be finer in the more Fe-rich orthopyroxenes in Binda.

The interpretation of the bulk chemical data used in this investigation (Chap. 5) indicated that Binda shows a greater affinity to the silicate portions of mesosiderites than to the cumulate eucrites and that its compositional resemblance to the magnesian howardites is largely coincidental. To test this further, averaged values for the primary, inverted, and exsolved

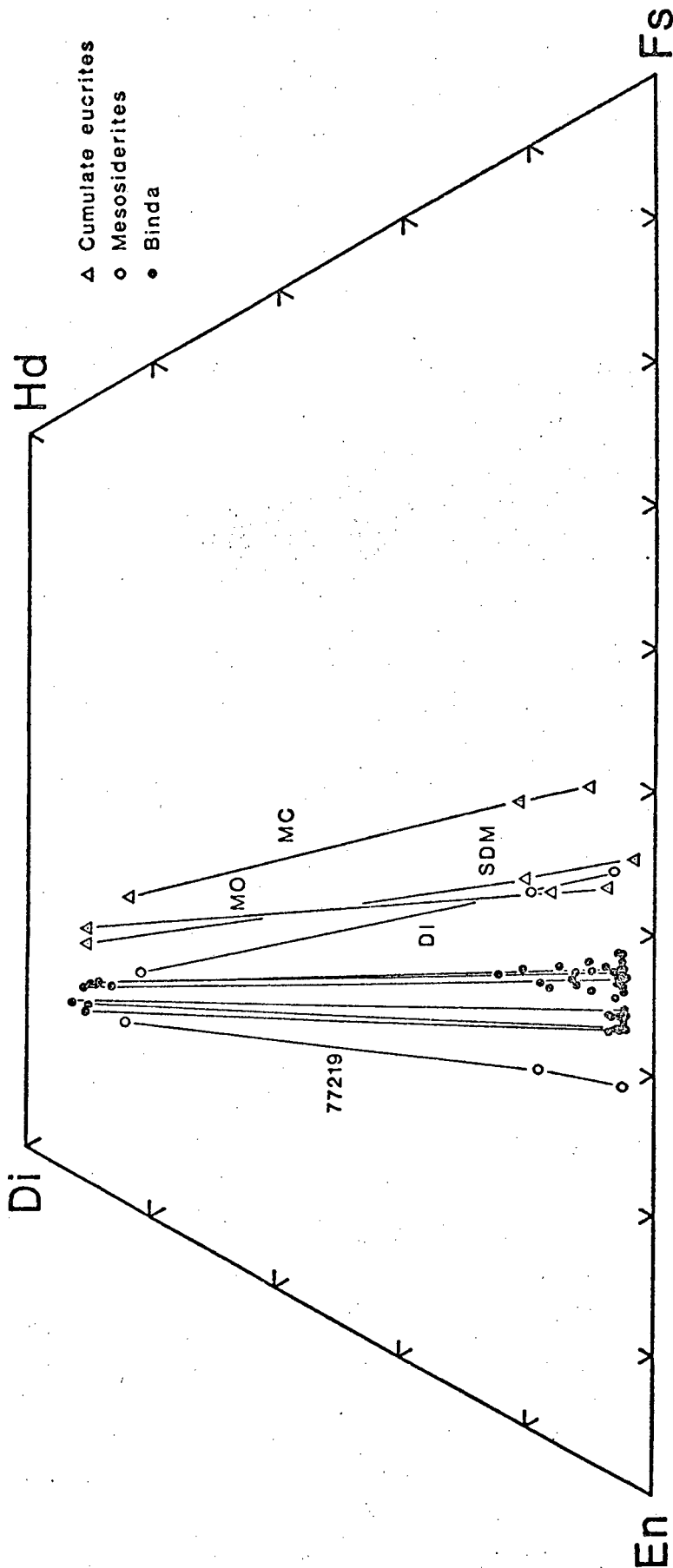


Fig. 7.8. Pyroxene compositions in Binda (mole %). The compositional range is small. The primary pigeonites have inverted to orthopyroxene with exsolution of coarse lamellae of Ca-rich clinopyroxene. Coexisting host and exsolved phases are linked by tie-lines, some of which were omitted for clarity. For comparison, averaged values of the original pigeonites, the host orthopyroxenes, and the exsolved phases in the cumulate eucrites and two mesosiderites (ALHA 77219 and Dyarrl Island) are also shown. Four other mesosiderites coincide with the Binda distribution and could not be plotted. (See text for details and sources of data on eucrites and mesosiderites.)

phases in pigeonites in the cumulate eucrites and certain mesosiderites taken from the literature were plotted in Fig. 7.8. Data for Moama were obtained from LOVERING (1975), and for Serra de Magé and Moore County from HARLOW *et al.* (1979). Mesosiderite pyroxenes plotted came from studies of the Antarctic mesosiderite ALHA 77219 (AGOSTA *et al.*, 1980) and Dyarri Island (HEWINS, 1979b). Pyroxenes from Estherville, Łowicz, and Morristown (also analyzed by Hewins) coincide with the magnesian end of the Binda range and could not be shown in Fig. 7.8. This position, incidentally, would be occupied also by the pyroxenes of the most Fe-rich diogenite yet discovered, Yamato 75032 (TAKEDA *et al.*, 1979b); pyroxenes in normal diogenites, e.g. Johnstown, plot at En_{72} to En_{74} (FLORAN *et al.*, 1977). Orthopyroxenes in Patwar range from En_{59} to En_{73} , and therefore include the Binda host compositions (WEIGAND, 1975). ALHA 77219 plots close to Binda on the magnesian side, but Dyarri Island, which is not a typical mesosiderite (see section 5.3.2), plots close to the pyroxenes of Moama and Serra de Magé. As a group, therefore, the pyroxenes of the three cumulate eucrites are compositionally distinct from those of Binda which, on the other hand, fall within the range exhibited by the mesosiderites and in fact coincide with the pyroxenes of certain mesosiderites selected only on the basis of availability of data. This provides supplementary evidence in support of the earlier-stated conclusions on the true classification of Binda.

Bununu

The pyroxenes in Bununu show a far wider spectrum of compositions than their counterparts in Binda (Fig. 7.9). They range from Mg-rich orthopyroxenes (En_{86}) to uninverted pigeonites with a substantial content of Ca (about Wo_{20}) in an almost continuous smoothly-curving trend that ends at about En_{30} . The concentration of orthopyroxenes is greatest in the range En_{77} to En_{64} . Exsolution of some of the pigeonites is evident in the figure;

co-existing host and lamellar phases are linked by tie-lines, and orthopyroxenes formed by inversion of pigeonite continue the low-Ca trend of the more magnesian primary varieties. The exsolved phase exists as fairly fine lamellae (section 3.3.2) and too few could be analyzed to establish the existence of a complementary high-Ca trend, though this is suggested in Fig. 7.9.

The disposition of Bununu's pyroxenes in the quadrilateral is similar to the crystallization trends of pyroxenes in slowly-cooled terrestrial tholeiitic intrusions (see, for instance, CARMICHAEL et al., 1974, p. 268, Fig. 5-27). From a knowledge that these pyroxenes are constituents, or parts of constituents, of a polymict breccia, one is justified in supposing that the source rocks for the breccia were related to one another by processes of igneous differentiation generally similar to the terrestrial analogue. The presence of both inverted and uninverted pigeonites in Bununu may indicate that the source rocks crystallized in two different cooling regimes. This may not be so, however, because although inversion is general in slowly-cooled igneous bodies, uninverted cumulus pigeonite occurs in the Middle Zone of the Skaergaard Intrusion and at a similar level in the Palisades Sill (COX et al., 1979, p. 304).

Fig. 7.10 shows the distribution of pyroxenes in Bununu that occur as constituents of lithic clasts (mainly plagioclase-pyroxene rocks) and as inclusions in glassy microbreccias. These distributions are similar to one another and to that of all the pyroxenes in the meteorite, indicating compositional similarity between the series of source rocks that supplied the pyroxenes occurring as single crystal clasts and the source materials from which the lithic clasts were derived. Also apparent are the facts that the compositional ranges are roughly the same whether the pyroxenes are situated in the 'matrix' or whether they occur as mineral and lithic inclusions in

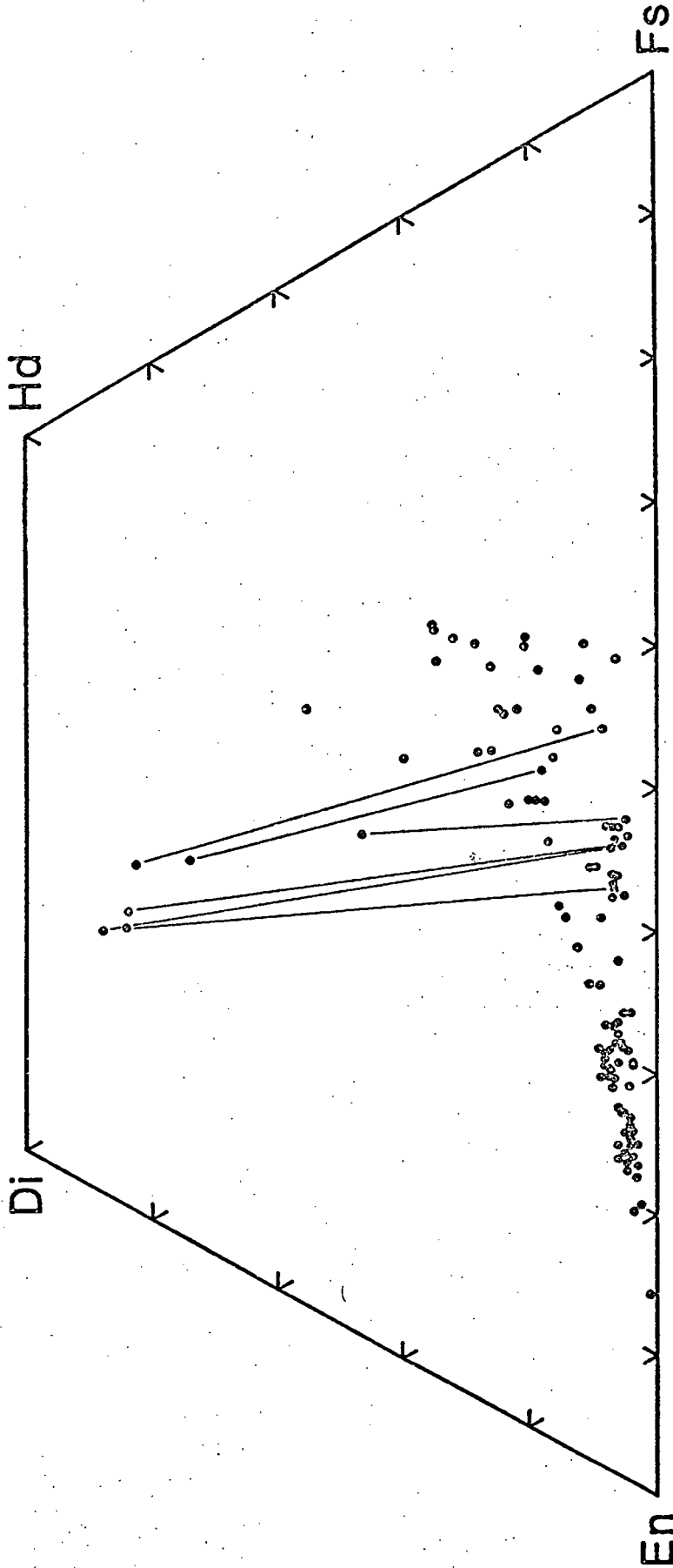


Fig. 7.9. Compositions of all pyroxenes analyzed in Bununu (mole %). A trend from magnesian orthopyroxene to uninvolved ferropigeonite is evident, but inversion of some pigeonites to Ca-poor host phases and exsolved augitic lamellae has also taken place. Co-existing host and lamellar phases are linked by tie lines.

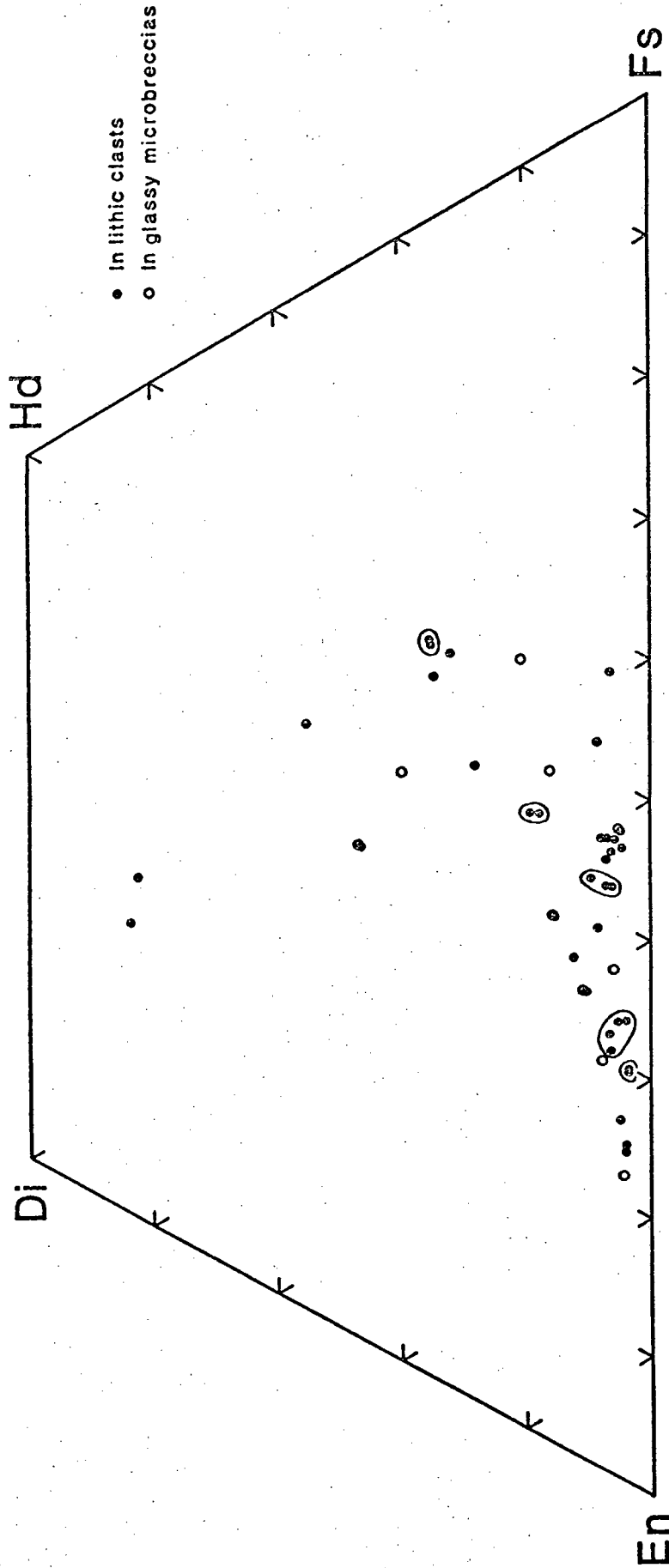


Fig. 7.10. Two distributions are shown: (a) that of pyroxenes included in glassy microbreccias in Bununu, and (b) that of pyroxene constituents of lithic clasts in the meteorite. Examples of pyroxenes from the same lithic clast are ringed, and show a high degree of equilibration. Both distributions are essentially similar to that of Fig. 7.9, which includes single mineral clasts also. This indicates that the same compositional ranges of rocks and minerals contributed to the Bununu breccia, and that these clastic constituents pre-dated formation of the glassy microbreccias.

the glassy microbreccias, and that the entire spectrum of fragmental material consisting wholly or partly of pyroxene was available for incorporation when the event(s) that formed the glassy microbreccias took place. Fig. 7.10 shows also that the pyroxenes in the lithic materials had attained equilibrium. The first appearance of plagioclase in the lithic clasts occurs at En_{58} .

Frankfort

The pyroxenes analyzed in Frankfort show a distribution similar to, but slightly less extensive than, that observed in Bununu. Notable differences are the higher proportion of magnesian orthopyroxenes in Frankfort, and the relatively low incidence of inversion in the pigeonites (Fig. 7.11). The uninverted pigeonites that form the more Fe-rich part of the trend extend to the same limit seen in the Bununu distribution (Fig. 7.9), i.e. about En_{30} . The compositional range determined in the present study is therefore far wider than that quoted by MASON et al. (1979) or by TAKEDA et al. (1976).

As noted in the petrographic study of this meteorite (Chap. 3), lithic clasts are not abundant. Some of the pyroxenes present in these clasts are plotted in Fig. 7.12 and, despite the sparseness of points in the quadrilateral, they show a compositional range almost as extensive as that of the preceding figure, albeit somewhat discontinuous. Only the most magnesian compositions are poorly represented, indicating that these are found mainly in single mineral clasts. The same feature is present in Bununu (Fig. 7.10), and implies that material easily recognizable as diagenitic is scarce, as noted for all four howardites examined petrographically. Frankfort is deficient also in lithic pyroxenes from the other end of the compositional range by comparison with Bununu, probably indicating slight differences in the source materials that contributed to these meteorite breccias. Equilibration is poor in the lithic clasts in Frankfort. Plagioclase may have joined the crystallization sequence at En_{66} , but is definitely present in association with orthopyroxene of composition En_{48} .

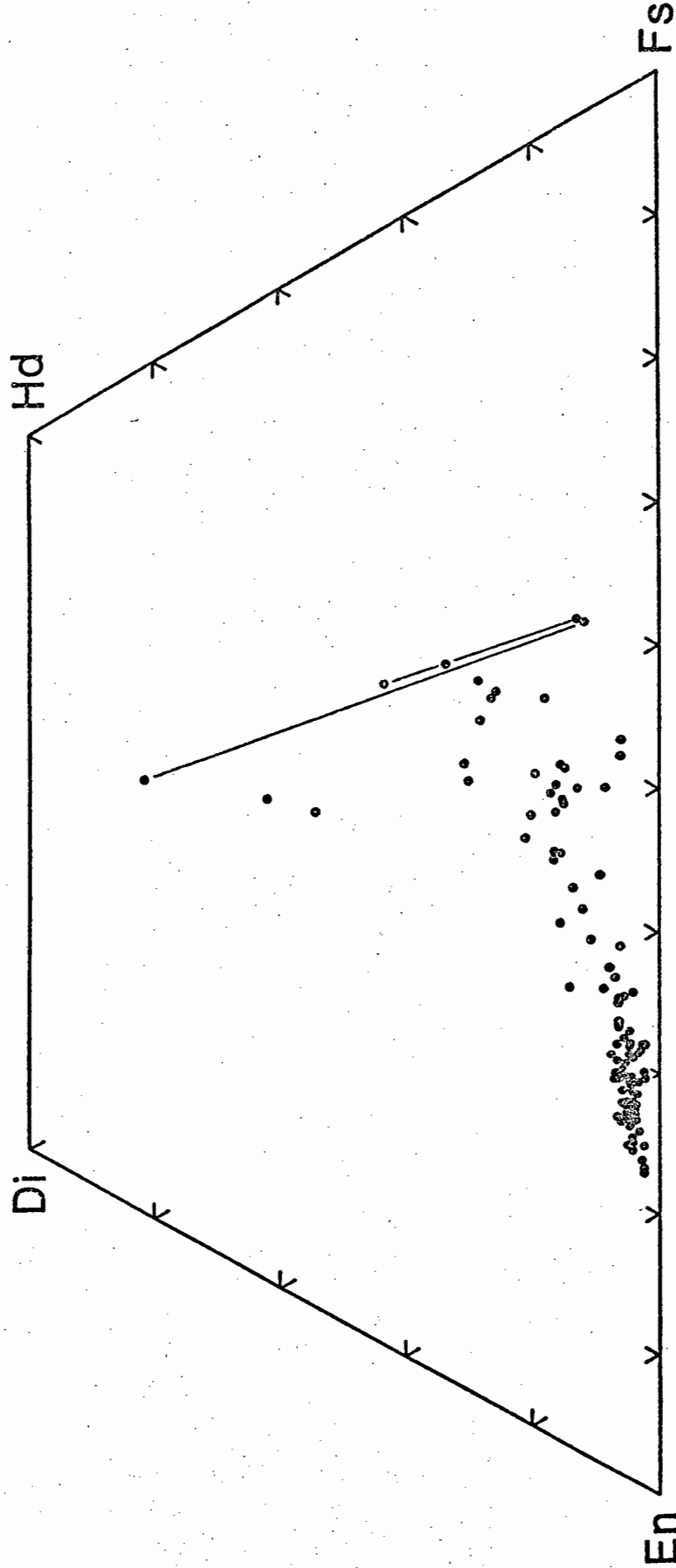


Fig. 7.11. The distribution of all pyroxenes analyzed in Frankfort. It is similar to that of Bununu though slightly less extensive and containing a higher concentration of magnesian orthopyroxene. Most of the clinopyroxenes are uninverted. Tie-lines in the figure join host and lamellar phases in two inverted pigeonites. As noted in Bununu, the low-Ca trend terminates at about En₃₀.

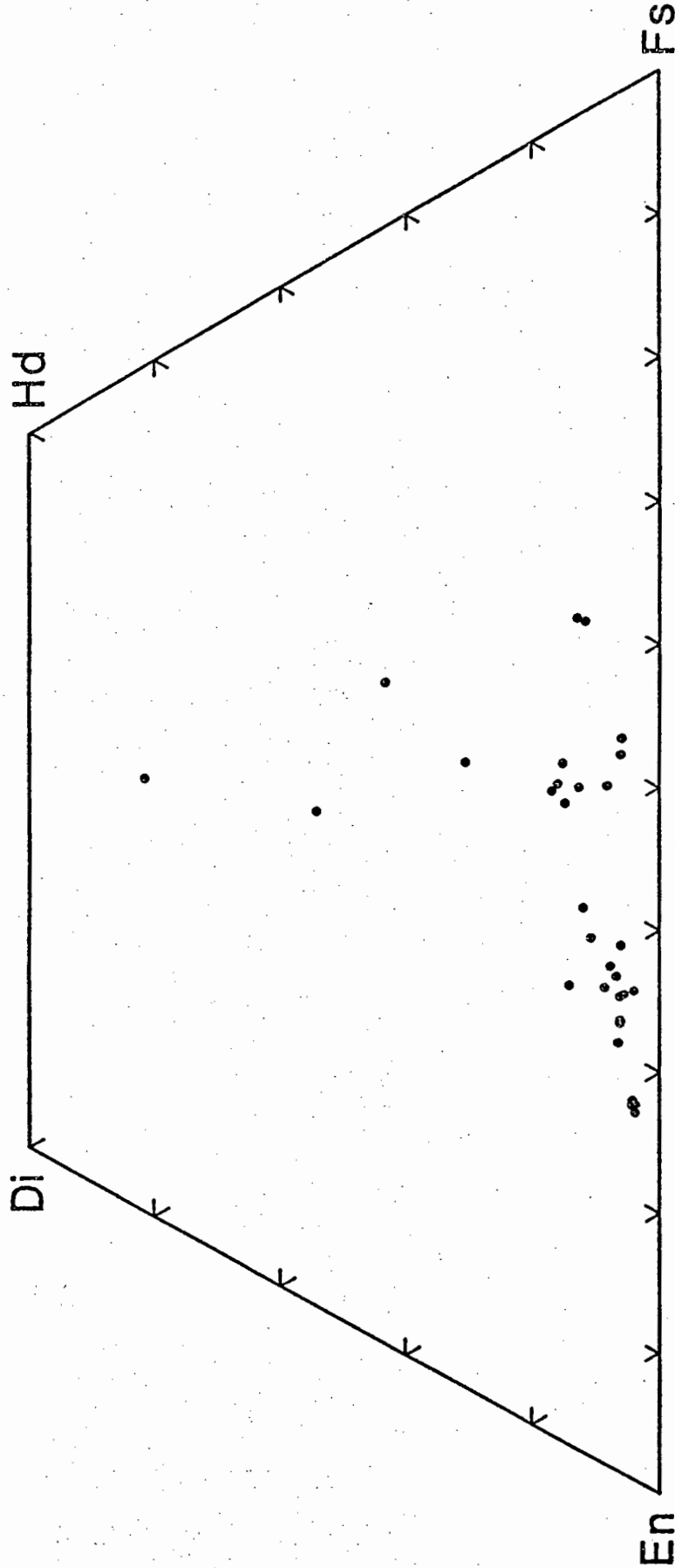


Fig. 7.12. Pyroxene compositions in lithic clasts in Frankfort. The distribution resembles that of the preceding figure in that the trend is visible though discontinuous and deficient in compositions representing both extremities of the compositional range. The high concentration of magnesian orthopyroxene seen in Fig. 7.11 is evidently composed of mineral, not lithic, clasts.

Malvern

Malvern shows the greatest petrographic diversity of the five non-chondritic meteorites studied, and this is reflected in the mineral chemistry of its pyroxenes, which were extensively analyzed (Table 1.2). All compositions were plotted in the quadrilateral (Fig. 7.13) and show the same trend as the pyroxenes in Bununu and Frankfort. As noted previously, an attempt was made in the Malvern analytical programme to distinguish between ortho- and clinopyroxenes, and this is reflected in Fig. 7.13 only. The figure includes also compositional data on the rare olivines in the meteorite.

The large number of analyses available makes it clear that the pyroxene trend is continuous from En_{86} to about En_{30} (as in Bununu and Frankfort), and that steps occur at En_{74} and at about En_{60} , where pigeonite makes its appearance. The latter step is shown in the same position in Fig. 5-27 of CARMICHAEL et al. (1974), but the terrestrial example shows no step where the former occurs in the Malvern trend. This may, however, be a consequence of the smaller number of analyses available for defining the terrestrial crystallization trend. The extent of the pyroxene trend of Fe enrichment in the howardites so far discussed (and in Molteno: see below) corresponds with the disappearance of pigeonite from the crystallization sequence observed in the Bushveld Igneous Complex, i.e. the limit of the two-pyroxene field, which occupies different positions in different terrestrial intrusions (CARMICHAEL et al., 1974). In Malvern, only limited inversion of pigeonite appears to have taken place until close to the Fe-rich end of the trend. There is a region of overlap at the transitional step between orthopyroxenes and pigeonites showing that although the lamellar exsolved phase could not be analyzed, inversion evidently occurred. However, the low-Ca trend does not extent beyond this region (Fig. 7.13). Near the limit of pigeonite crystallization, exsolution of a Ca-rich phase did take place, but for the most part on a

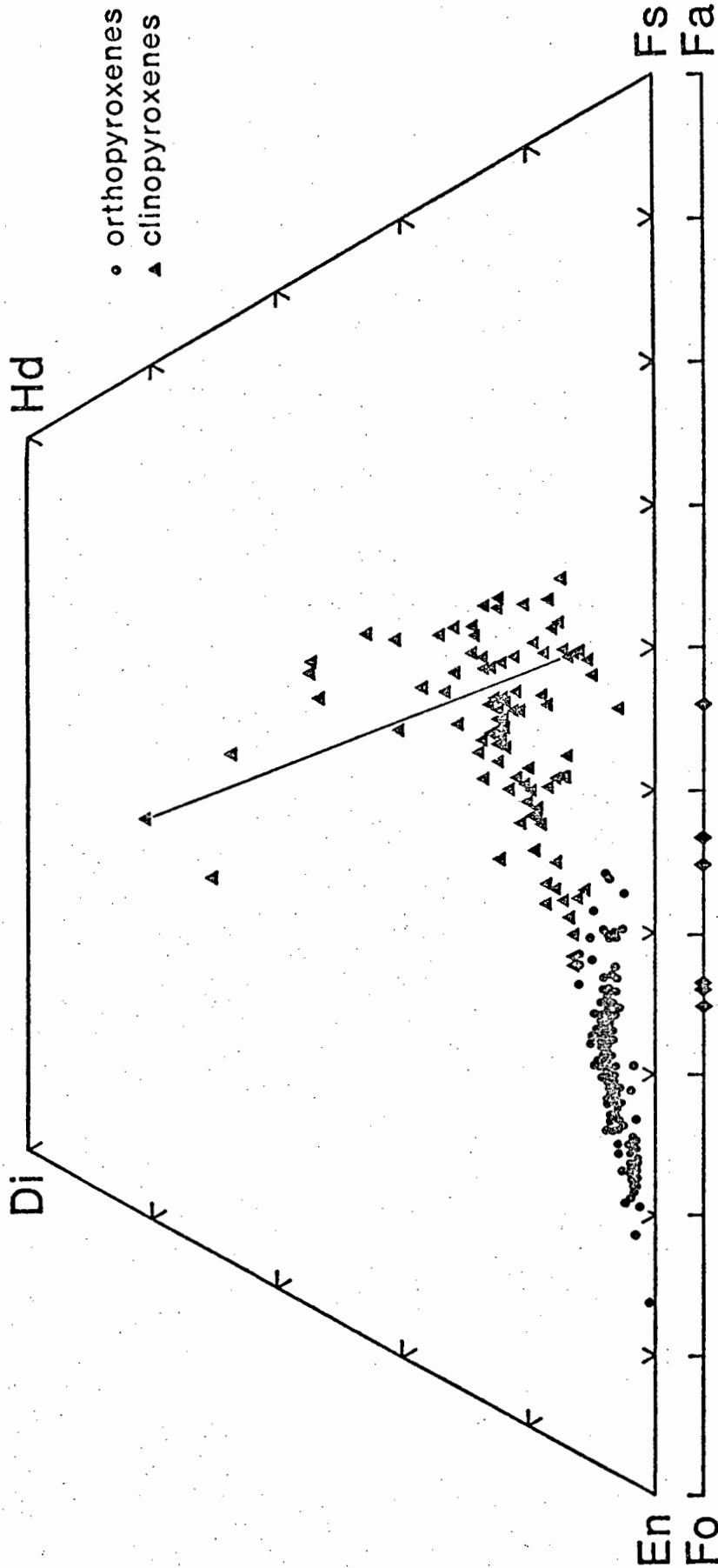


Fig. 7.13. The compositions of all pyroxenes analyzed in Malvern, a distinction having been made between ortho- and clinopyroxenes at the time of analysis. The continuity of the trend is evident, though steps are present in the magnesian orthopyroxenes at En_{74} and between ortho- and clinopyroxenes at about En_{60} . Pigeonite crystallization ceases at about En_{30} ; for a discussion of this and the limited degree of inversion in the Malvern pyroxenes, see the text. The compositions of the rare olivines in Malvern are also shown in this figure.

scale too fine to be resolved by the microprobe. These finely-lamellar pyroxenes retain the optical properties of pigeonite but plot in a scattered fashion in Fig. 7.13 because of the variable amounts of exsolved material included in the volume analyzed by the probe. In only one lamellar pyroxene in a lithic clast could successful analyses of a host-lamella pair be performed; they are joined by a tie-line in Fig. 7.13.

As in the previous examples, the Malvern pyroxenes were examined in relation to their modes of occurrence (Figs 7.14 and 7.15). Those occurring as constituents of lithic clasts show a distribution similar to that of Fig. 7.13, lacking only the most magnesian compositions. Co-existing pyroxenes appear to be in equilibrium with one another (circled points in Fig. 7.14). The relatively small number of analyses in this figure emphasizes the fact that the majority of pyroxenes in Malvern occur as clasts in the 'matrix' or as inclusions in glassy materials. Plagioclase makes its appearance in association with orthopyroxene of composition En_{67} in the large cumulate clast described in section 3.3.2 and illustrated in Plate 3.3 D. The pyroxenes analyzed in this clast plot as the largest concentration of outlined points in Fig. 7.14.

Pyroxenes occurring as inclusions in glassy microbreccias in Malvern show practically the full compositional range and lie on a smooth evolutionary curve largely uncomplicated by exsolution (Fig. 7.15). The compositional variety present confirms the observation made on similar included pyroxenes in Bununu, viz. that the entire range was available for incorporation in the glassy microbreccias when they were formed. A further conclusion can be drawn because of the larger sample of such pyroxenes analyzed in Malvern: a very considerable spread of compositions (almost the full range) can be found in a single glassy microbreccia clast (Fig. 7.15), indicating that no re-equilibration of included pyroxenes took place. A similar conclusion was

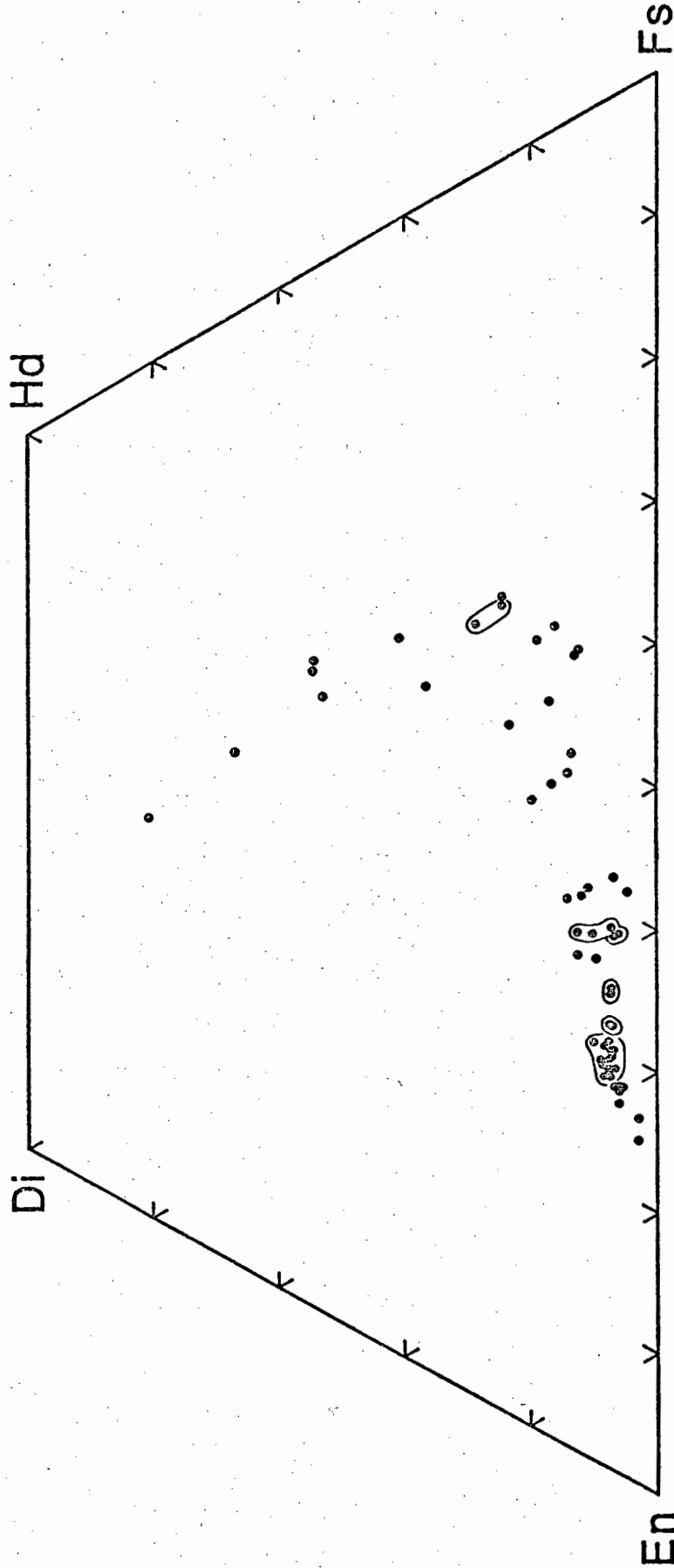


Fig. 7.14. Pyroxene compositions in lithic clasts in Malvern. These pyroxenes make up a fairly small portion of the total number analyzed, but show almost the same distribution as depicted in Fig. 7.13. The most Mg-rich compositions are absent or poorly represented. Co-existing pyroxenes are outlined, and show a high degree of equilibration. The largest group of circled analyses are those of pyroxenes in the pyroxene-plagioclase adcumulate clast pictured in Plate 3.3 D.

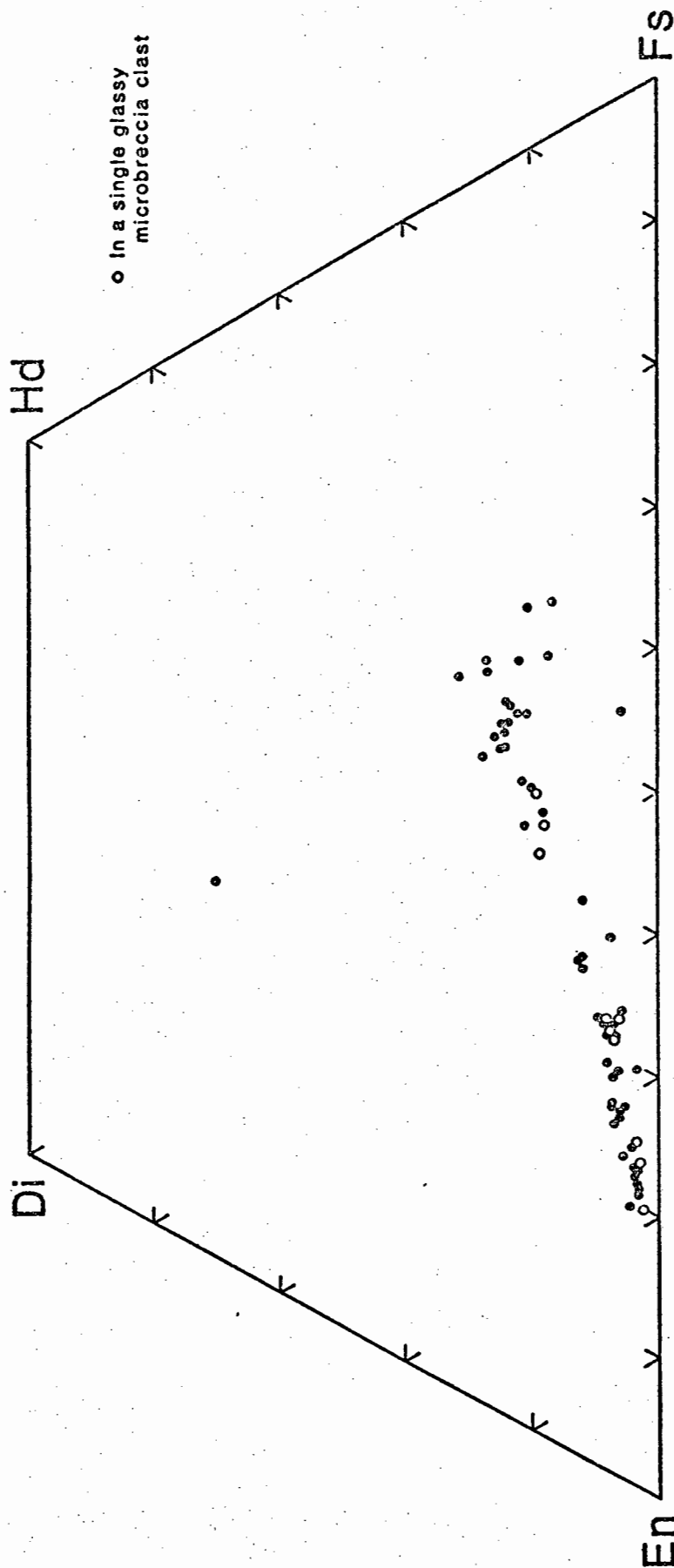


Fig. 7.15. The compositional range of pyroxenes included in glassy microbreccias in Malvern encompasses all but the most extreme compositions and defines a clear, continuous evolutionary trend. Few of the inclusions show evidence of inversion. No re-equilibration of included pyroxenes took place, as proved by the range of compositions present in a single glassy microbreccia clast.

arrived at in respect of plagioclase inclusions in both Malvern (Fig. 7.3) and Molteno (Fig. 7.2).

Molteno

Fig. 7.16 shows the full range of pyroxenes analyzed in Molteno. It is similar to those already discussed, but the central part of the pyroxene evolutionary trend is less well defined than in the other three howardites. Furthermore, there appears to be a lesser degree of Ca-enrichment with increase in Fe than is present in the pyroxenes of Bununu, Frankfort, and Malvern. The most magnesian pyroxene analyzed has a composition of En_{82} , and the trend extends, as previously noted, to the limit of the two-pyroxene field (about En_{30}). Inversion in the pigeonites is not well defined but is obviously responsible for the scatter in the distribution of points at the Fe-rich end of the compositional spectrum. This is in agreement with the observation (section 3.3.2) that the exsolution lamellae in Molteno's pyroxenes are very thin.

Pyroxenes in lithic clasts show the full compositional range and a clearly-defined, if discontinuous, trend (Fig. 7.17). Those co-existing in the same clast have equilibrated completely (the outlined points in the figure). The discontinuities in the trend (some of which are inherited from the full distribution) are possibly attributable to sampling deficiencies. The first appearance of plagioclase (An_{95}) occurs at a composition of En_{61} in the pyroxene crystallization sequence.

Fewer pyroxenes included in glassy microbreccias were analyzed in Molteno than in the other howardites investigated mainly because these bodies are limited in extent and number, as discussed in section 3.3.2. However, they are distributed over a wide range of compositions (Fig. 7.18) and, as in the previous examples, the compositional variety of co-existing inclusions proves that re-equilibration did not take place.

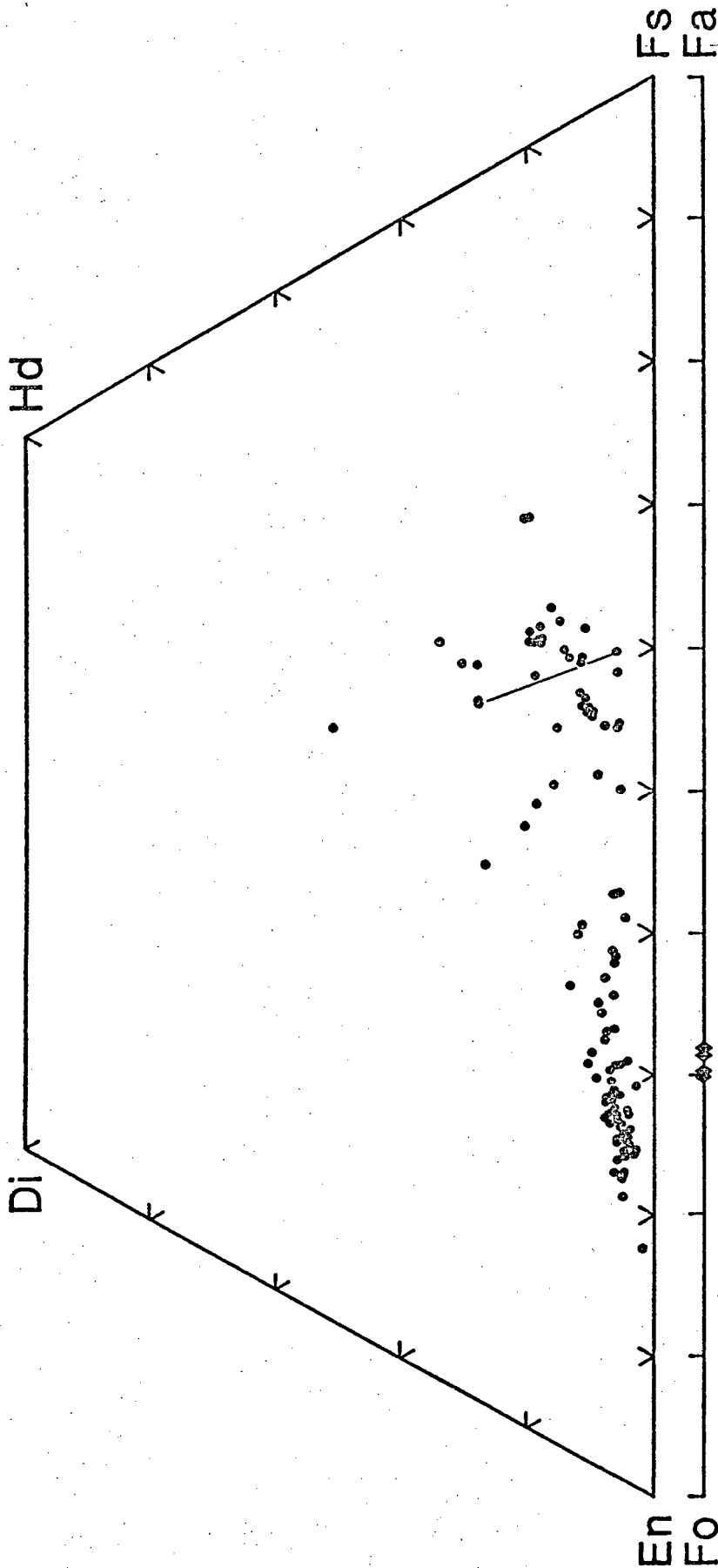


Fig. 7.16. The compositional range present in the pyroxenes of Molteno is similar to those of the other three howardites, but the crystallization trend is less continuous and may show a lower rate of enrichment in Ca with increase in Fe. Inversion, with accompanying exsolution of a Ca-rich phase, probably accounts for the scatter of points in the pigeonite part of the trend. The figure also shows the compositions of olivines present in Molteno.

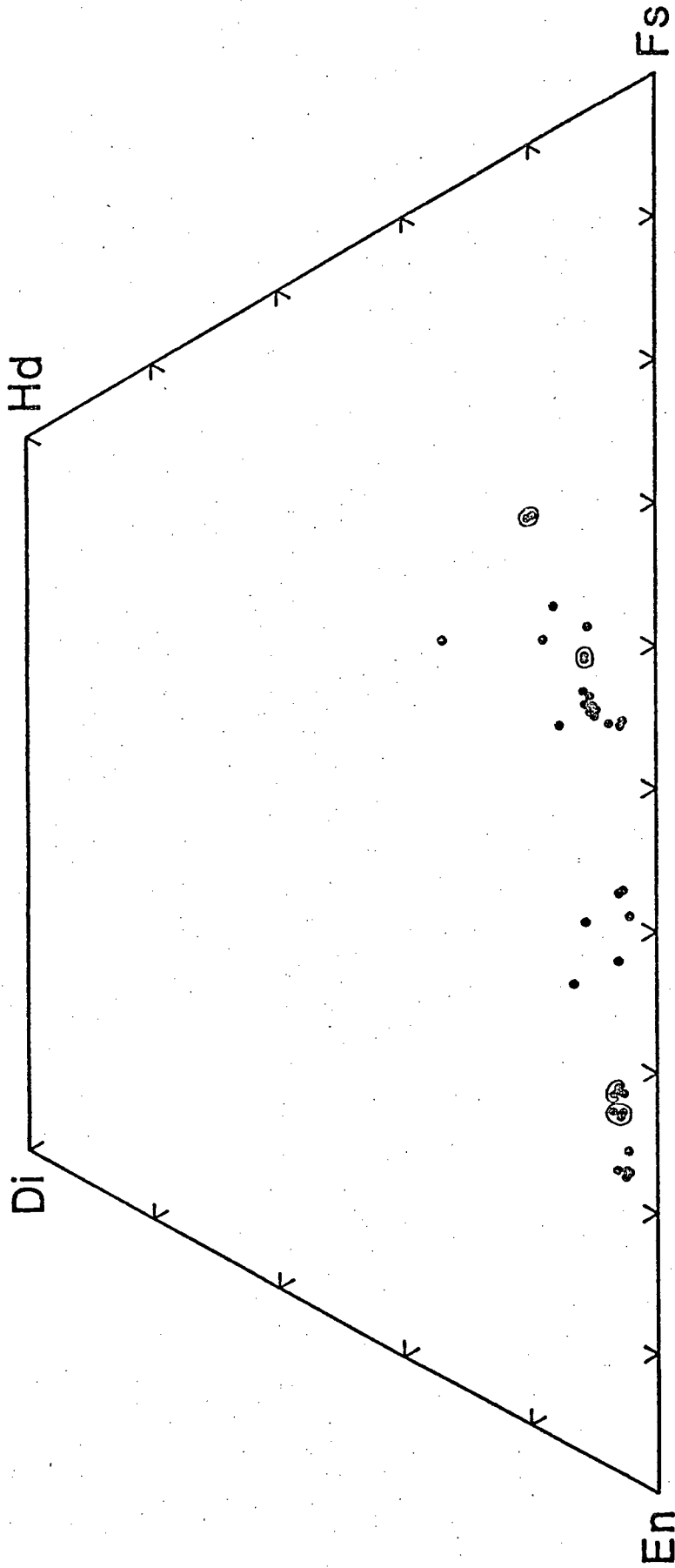


Fig. 7.17. Pyroxenes in lithic clasts in Molteno are distributed over the full range of compositions shown in the previous figure. Co-existing pyroxenes (circled) exhibit a high degree of equilibration. Breaks in the trend most probably reflect the limited availability of lithic material for analysis.

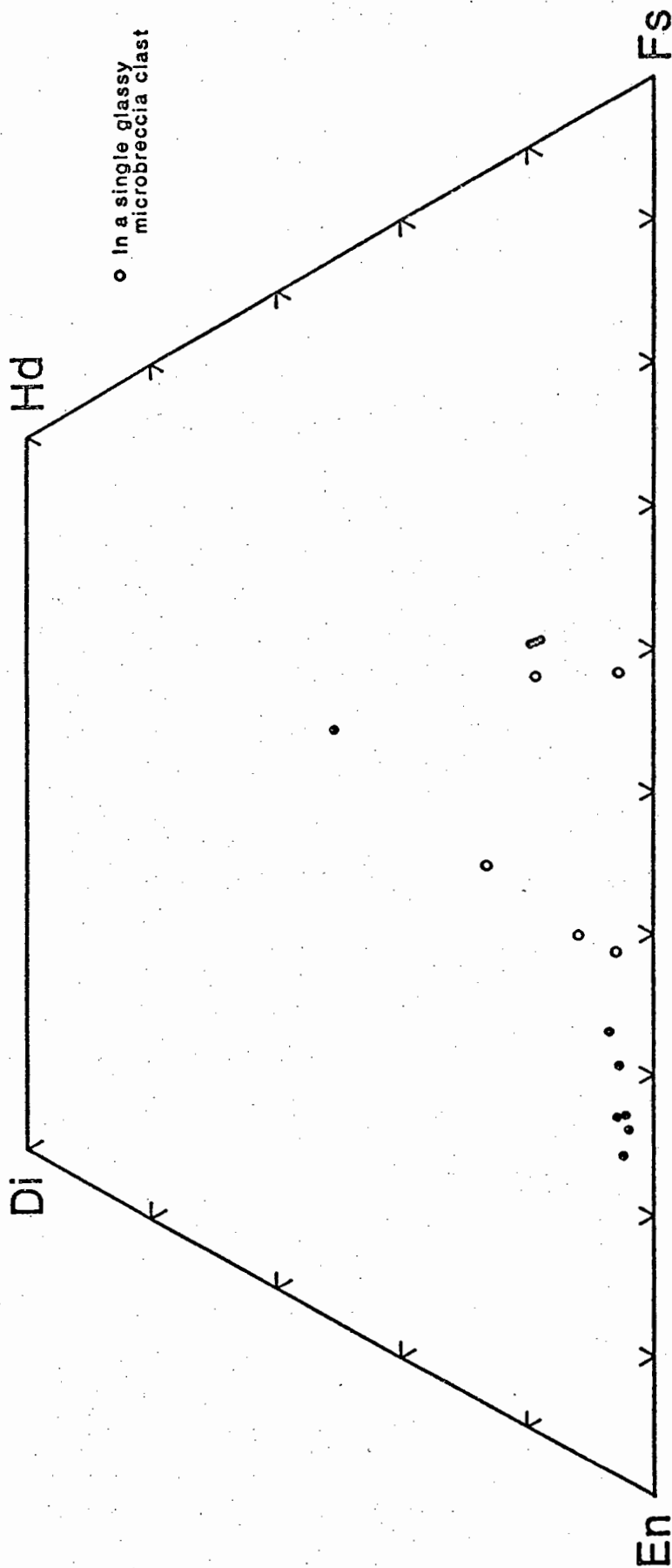


Fig. 7.18. Pyroxene inclusions in glassy microbreccias in Molteno, though sparse, show a wide range of compositions. Re-equilibration of these inclusions has not taken place.

7.2.4 Bimodality in the major constituents of the howardites studied

One of the stated aims of the study of the mineral chemistry of the four howardites was to check for evidence that would support or refute the hypothesis of JÉROME and GOLES (1971) that these meteorites are mixtures of eucrites and diogenites. This can be considered at this point in the light of the new data on the major constituents - plagioclase and pyroxene - of these howardites, which are representative of the wide compositional range characteristic of their class (see the inter-element relationships plotted in Chap. 5), and of the views held on the compositions of the eucrite and diogenite classes at the time that the hypothesis was formulated. These postulated end-members of the mixing sequence were regarded as monomict (or unbrecciated) assemblages of plagioclase and pyroxene in the first instance, or pyroxene alone in the second, both classes having very restricted compositional limits. It would therefore be reasonable to expect, if two such mineralogically and chemically distinct end-members were mixed, a sharply bimodal distribution of compositions in the major constituent common to both, viz. the pyroxenes. The plagioclases might be expected to display a unimodal normal distribution, or a close approximation thereto if allowance were made for natural variation in the eucrites. Instead, they show a continuous variation over a fairly wide range of compositions (Fig. 7.1) in keeping with the conclusion demonstrated in the present work (Chaps 5 and 8) that the eucrites constitute a differentiation series, not a class with very narrow compositional limits. This conclusion is further strengthened by the coherence that exists between the chemical variations in plagioclases and pyroxenes co-existing in lithic fragments in the howardites (Fig. 7.19); the example given is Malvern. Such sympathetic variation between CaO and MgO, used as parameters of crystallization in the plagioclases and pyroxenes respectively, provides a strong argument in favour of these lithic clasts having had their origin in a

Fig. 7.20. Al-Ti-Cr relationships in the pyroxenes of Binda and Bununu.

Binda: The Binda pyroxenes show a well-developed trend that is interpreted as the later part of the crystallization sequence seen in howarditic pyroxenes. The trend suggests that some degree of fractionation did occur in Binda, as indicated by other parts of the investigation. The Ti-enrichment in these pigeonites is directly correlated to decrease in Mg and concomitant increase in Fe (see Fig. 7.8). Host-lamellae pairs plot in almost coincident positions. The significance of the lines 'a' and 'b' is explained in the text.

Bununu: The full trend is displayed by the pyroxenes in this and the other two howardites studied (Fig. 7.21). One limb of the inverted V shows depletion of Cr, probably caused by crystallization of chromite along with the magnesian orthopyroxenes that plot in this part of the trend. The change in direction of the trend occurs at the point at which plagioclase joins the crystallization sequence, removing Al from the melt. Depletion in Cr continues, but to a lesser degree than in the earlier crystallization. Pigeonites dominate the later stages of the evolution of the source rocks and provide suitable structures for the Ti-enrichment that accompanies the depletion in Al. The scatter of points within the inverted V represents pyroxenes at the limit of the two-pyroxene field in which exsolution was not completely resolved by the electron microprobe.

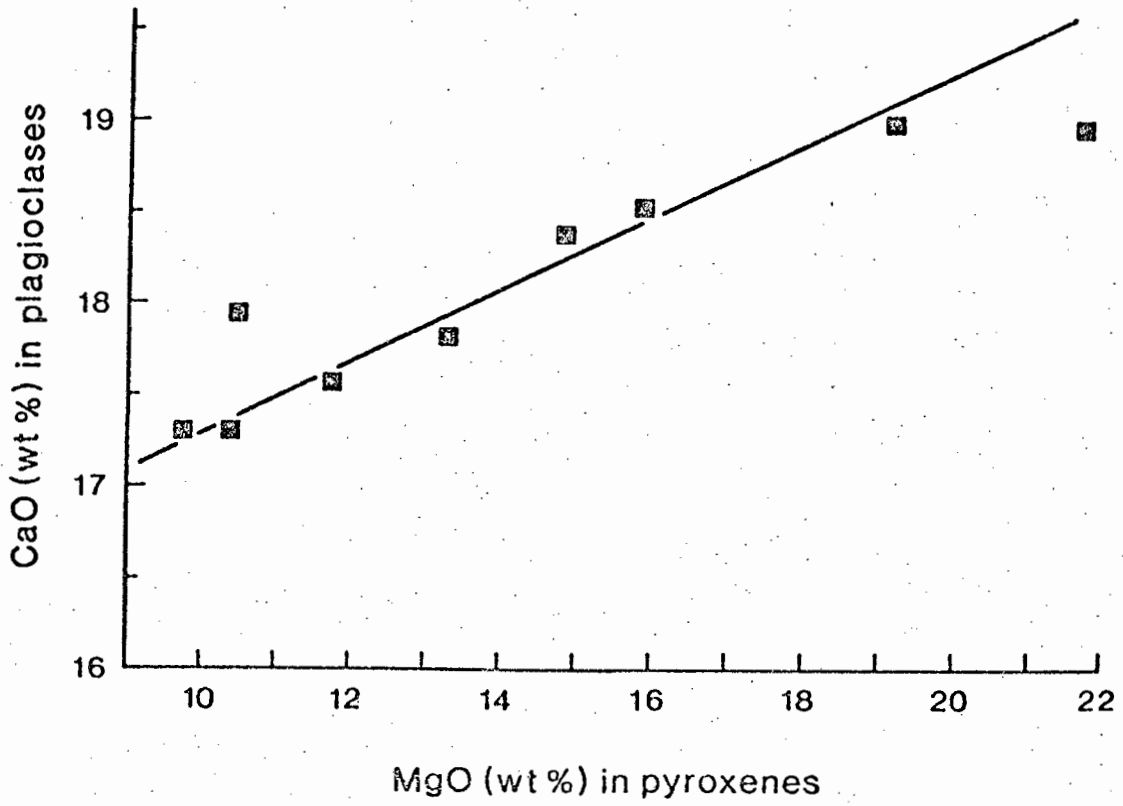


Fig. 7.19. The coherence between variations in the CaO content of plagioclases and MgO in pyroxenes co-existing in lithic clasts in Malvern. This relationship strongly suggests that the source rocks of the clasts were genetically linked by differentiation.

series of differentiated rocks, i.e. the eucrites, as they are considered in the present study. The implications of this wider definition of the eucrites will be discussed later, when a model for the formation of the achondrites is considered.

Because the trend established for the pyroxenes in the four howardites investigated by microprobe is essentially a converse relationship between Mg and Fe, bimodality in the distribution of the pyroxenes should be readily observable - if it is in fact present - in the quadrilateral plots that show all the pyroxenes analyzed in each howardite, i.e. Figs 7.9, 7.11, 7.13, and 7.16. However, the trends in all of these figures are essentially continuous. If present, discontinuities are minor and occur at different compositions in different plots, and are attributable to sampling. The plot for Malvern (Fig. 7.13) attests to this: if sufficient samples have been analyzed, there are no breaks in the trend. The present work therefore points to the conclusion that compositional bimodality does not exist in the pyroxenes of the howardites as is required by a formational hypothesis based on the mixing, in varying proportions, of two end-members with restricted compositions. On the contrary, gradation from the one extreme of the compositional spectrum to the other appears to be smooth and essentially continuous, with no marked modal concentrations. These conclusions were stated, in essence, for Malvern by SIMPSON (1974). A different view was presented for the same meteorite by DESNOYERS and JÉROME (1977).

7.2.5 Al-Ti-Cr relationships in the pyroxenes

The elements Al, Ti, and Cr are frequently neglected in pyroxene studies, emphasis being placed on variations in Ca, Mg, and Fe. In the present study, the pyroxenes of four of the non-chondritic meteorites were plotted in ternary diagrams after recalculation to atomic percent of Al, Ti,

and Cr. Malvern was omitted because of the inadequacy of data on Cr in its pyroxenes. The plots appear in Figs 7.20 and 7.21. Definite trends are present in each plot, those of the three howardites showing a close similarity to one another. The Binda trend is well developed and appears to coincide with the end section of the low-Cr limb of the inverted V-shaped trend of the howarditic pyroxenes (Fig. 7.20). Examination of the Binda data shows that the most magnesian compositions plot at the Al-rich end of the trend. Ti therefore increases, and Cr decreases slightly, with decreasing Mg. These variations are consistent with the contention stated earlier in this chapter that the plagioclases and pyroxenes in Binda show a small, but definite, degree of fractionation. The data further indicate that Al, Ti, and Cr played little part in the exsolution processes accompanying inversion of Binda's pigeonites; host-lamellae pairs plot in virtually the same positions in the ternary diagram.

Examination of the trends displayed by the three howardites reveals that they can be related to the crystallization sequence apparent in the pyroxene quadrilateral plots discussed earlier. The most magnesian compositions (orthopyroxenes) occur on the low-Ti limb of the inverted-V trend, with Mg decreasing progressively towards the apex. This change is accompanied by a corresponding increase in Fe and a slight increase in Ca. At the point at which pigeonite succeeds orthopyroxene as the primary pyroxene, the crystallization trend abruptly changes direction and the increase in Ca becomes more marked, while Mg continues to decrease along the low-Cr limb. Host-lamellae pairs plot on this limb in positions generally within a few percent of one another, the exsolved phase invariably being richer in Al and poorer in Ti than the host. Scattered points that fall in the inside of the inverted V (see particularly Bununu: Fig. 7.20) prove to be pyroxenes at the limit of the two-pyroxene field in which the exsolved lamellae have not been resolved

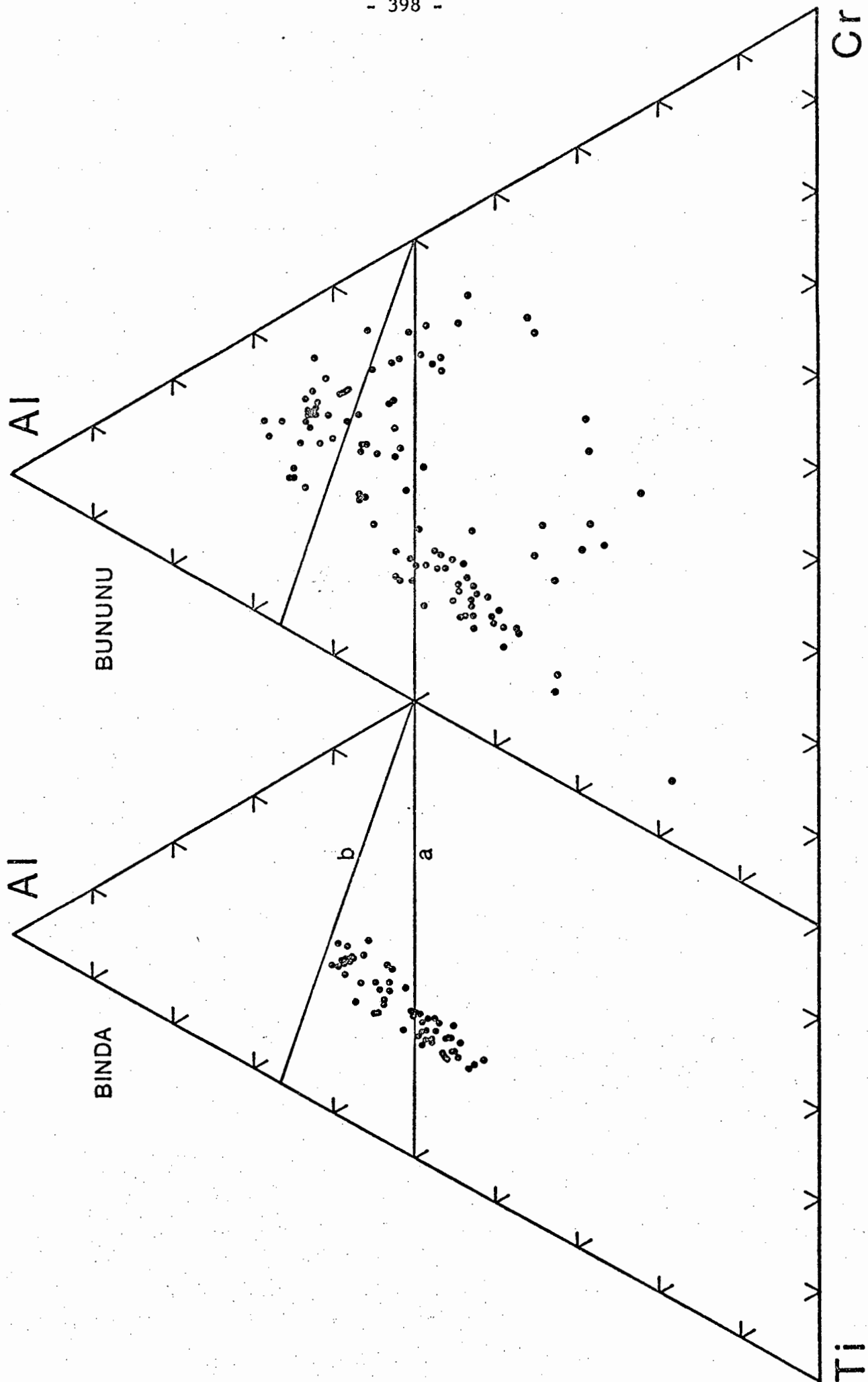
by the microprobe (cf. the earlier quadrilateral plots).

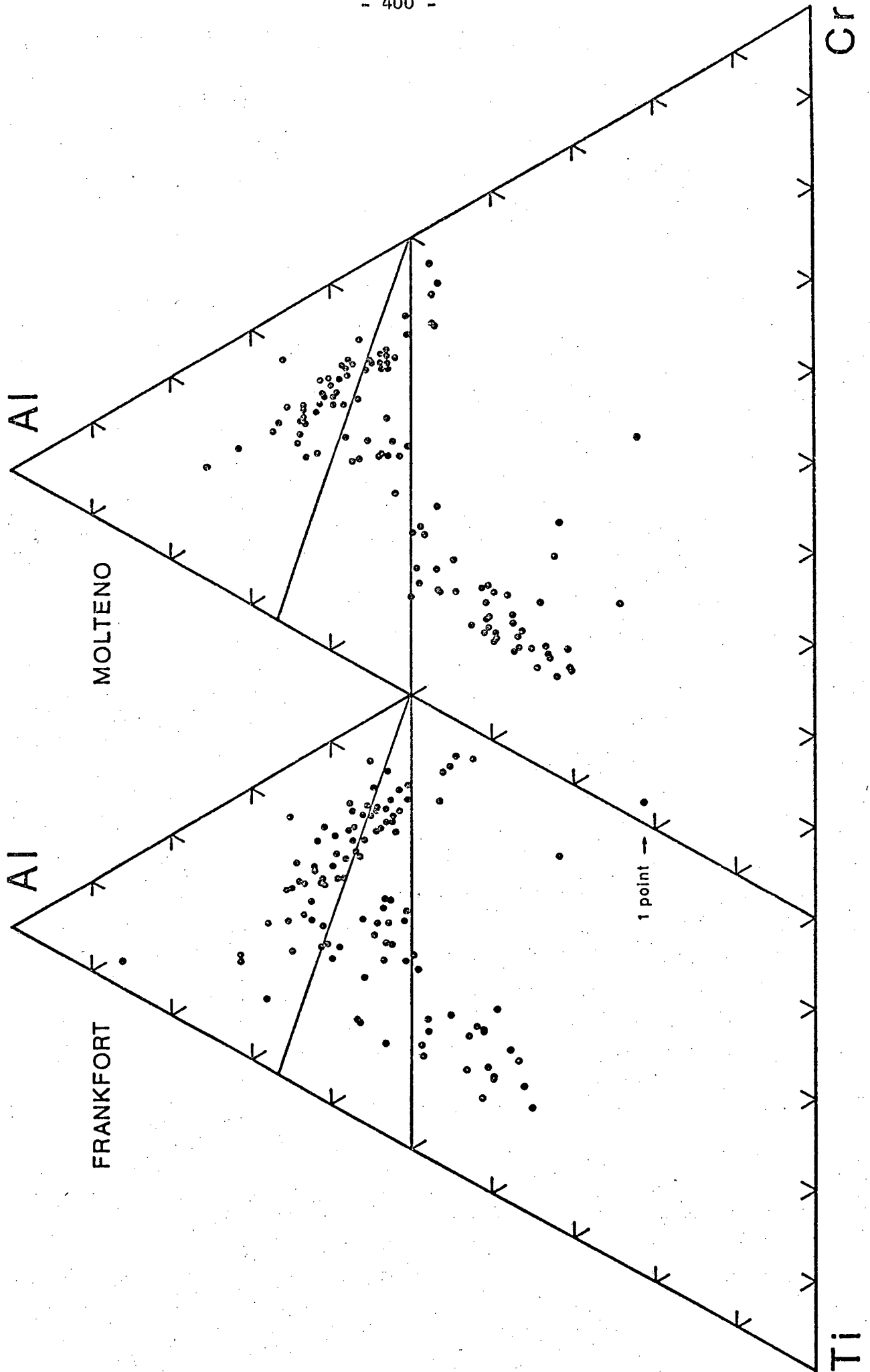
The evolutionary trends in the pyroxenes of howardites evident in the Al-Ti-Cr ternary diagrams are very similar to the compositional changes reported by HOLLISTER et al. (1971) in continuous zoning in pyroxenes in the Apollo 12 sample 12065. Further interpretation of the howarditic pyroxene trends draws heavily on the work of Hollister and his colleagues; their reasoning, and the assumptions on which it is based, are set out on p. 543 of the paper cited. The line 'a' in Figs 7.20 and 7.21 is that on which compositions with entirely trivalent Cr and Ti, charge-balanced by Al substitution for Si, will plot. Compositions below line 'a' contain some divalent Cr. Line 'b' defines compositions in which all Cr is trivalent, all Ti is quadrivalent, and none of the Al is in octahedral co-ordination in the mineral structure. Between the lines, Ti probably occurs in both valency states. Pyroxenes plotting above 'b' contain octahedrally co-ordinated Al.

Application of these principles to the pyroxenes under consideration shows that, as fractionation proceeded, Cr in the Binda pyroxenes changed from trivalent to divalent. This is in accordance with the tendency for Cr^{3+} to be partitioned into the earliest available octahedral co-ordination sites (TAYLOR, 1975). Likewise, Ti ions entering the structures of the later pyroxenes to crystallize were trivalent, not quadrivalent. The earlier, more aluminous, part of the Binda trend corresponds to the edge compositions in the pyroxenes of 12065. The lunar trend does not, however, extend beyond line 'a' and presumably Cr^{2+} is not present.

The extension of the later part of the crystallization trend into the area of divalent Cr is even more marked in the three howardites. In other respects, it resembles the lunar example (Fig. 8 of the Hollister paper) but for a possible slight displacement towards the Al-Cr side of the ternary. A few of the most magnesian compositions plot below line 'a', in a

Fig. 7.21. Al-Ti-Cr relationships in the pyroxenes of Frankfort and Molteno. Both ternary diagrams show the fully developed trend discussed in the previous figure. Further consideration of the implications of this trend in terms of the crystal chemistry of the pyroxenes of howardites is contained in the text.





position corresponding to the hypersthene cores in the pyroxenes of sample 12065. According to the interpretation of Hollister and his colleagues, these early-crystallizing howarditic pyroxenes should contain divalent Cr. This is in general agreement with the statement of TAYLOR (1975) that the trivalent ion does not enter into orthopyroxene, but does not explain why so few of the orthopyroxenes that make up the greater part of the low-Ti limb of the trend plot below line 'a'. Crystallization in this limb is directed away from the Cr vertex, indicating depletion of the melt by co-precipitation of chromite, which was observed as inclusions in pyroxenes in the howardites (section 3.3.2). In the later stages of crystallization, i.e. in that part of the limb above line 'b', the concentration of Al increases to the point that it occupies octahedral sites and either $\text{CaAl}_2\text{SiO}_6$ (Ca-Tschermak's molecule) is present in solution in the pyroxenes (HOLLISTER et al., 1971) or exsolution (possibly sub-microscopic) of diopside or diopside augite takes place.

The change in direction of the trend occurs at the point at which plagioclase enters the crystallization sequence, closely followed by the appearance of primary pigeonite. The trend veers away from the Al apex as the melt becomes progressively depleted in Al by the precipitation of plagioclase. Enrichment in Ti ensues as a result of the availability of the clinopyroxene structure, into which it is readily partitioned. Depletion of Cr continues, but on a reduced scale. The Binda trend (Fig. 7.20) also shows these element patterns, but the complete absence of octahedral Al indicates that crystallization of plagioclase and pigeonite occurred simultaneously.

A further implication of the trends seen in Figs 7.20 and 7.21 is that the ratio $\text{Ti}^{3+}/\text{Ti}^{4+}$ changes as crystallization progresses. In particular, it increases with enrichment in Ti in the pigeonites that appear in the later stages of crystallization, according to the interpretation of HOLLISTER

et al. (1971). The presence of high $\text{Ti}^{3+}/\text{Ti}^{4+}$ ratios in titaniferous pyroxenes from Apollo 11 and Apollo 17 mare basalts was demonstrated by SUNG et al. (1974). These authors suggested two possible processes that, operating in conjunction with the low oxygen fugacities that prevailed during the crystallization of these rocks, might have given rise to high concentrations of Ti^{3+} ions. These were (a) pressure-induced reduction of quadrivalent Ti caused by the depth at which the titaniferous magma was generated by partial melting, and (b) shock-induced reduction of Ti^{4+} by impacting planetary objects. Of these, the first appears the more plausible in the present instance. It is difficult to see why all the pyroxenes in Binda and the three howardites do not show substantial amounts of Ti^{3+} because all have undergone shock attributed to impact (see section 3.3.3).

Note that, as in most discussions of evolutionary processes in this report, development of trends has been treated according to a fractional crystallization model. This has been done to reduce the complexity of the arguments presented, but does not necessarily imply that fractional crystallization was the only mechanism that operated. For this reason, arrows indicating the directions of evolutionary trends have been omitted from the diagrams, including Figs 7.20 and 7.21. The presumed course of events followed in the genesis of the achondrites is discussed in Chap. 9.

7.2.6 FeO/MnO relationships in the pyroxenes

The close coherence of the oxide pair FeO-MnO was first noted in lunar samples by LAUL et al. (1972), and further work by SCHMITT and LAUL (1973) indicated that howardites and eucrites do not plot on the linear correlation trend of the lunar rocks and were therefore unlikely to be of lunar origin. WÄNKE et al. (1973) showed that the relationship is applicable also to terrestrial rocks and meteorites, but that the FeO/MnO ratio varies

considerably between these groups; for the Moon, it is 80, for terrestrial samples 60, for achondrites and the silicate phase of H- and L-chondrites 35, and for the silicate fractions of mesosiderites it is 24.

These observations made on bulk rocks and meteorites caused DYMEK et al. (1976) to examine the FeO/MnO ratio in the pyroxenes of Kapoeta and to show the existence of a very good linear correlation (their Fig. 11) with a slope of 35, identical to that of the bulk howardite because virtually all the Fe and Mn had been partitioned into the pyroxenes. By contrast, lunar pyroxenes proved to have ratios of about 60 because of the competition for Fe and Mn presented by olivine and ilmenite. More recent studies of the relationship in meteoritic minerals have been concentrated on the pyroxenes and olivines of mesosiderites and are therefore outside the scope of the present investigation, but a significant observation was made by HEWINS (1979b). He withdrew a previous conclusion (HEWINS et al., 1977) that the FeO/MnO ratios of the pyroxenes in achondrites and mesosiderites are characteristic of these meteorite groups, i.e. 35 for the achondrites and 24 for the mesosiderites. This step was occasioned by recognition of the range of values present in the achondritic pyroxenes analyzed by DYMEK et al. (1976) and TAKEDA et al. (1976). This section therefore addresses the problem and presents the results of a study of the FeO/MnO ratios in the pyroxenes of the five meteorites analyzed by microprobe, and a comparison of these values with the ratios calculated from the bulk analyses of the 42 meteorites included in the investigation (Table 7.1).

The average values for the FeO/MnO ratios of the pyroxenes in the five meteorites, listed with their associated standard deviations and ranges in Table 7.2, show no significant departure from the figure of 35 previously established for achondritic pyroxenes. This parameter does not distinguish the Binda pyroxenes from those of the howardites. The wide variations

Table 7.1. FeO/MnO (wt) ratios in the meteorites included in this investigation

METEORITE	FeO/MnO (wt)	METEORITE	FeO/MnO (wt)
<u>Table 4.2</u>			
Malvern (UCT)	32.77	Moama	29.70
Malvern (BLM)	34.02	Moore County	33.15
Binda	31.82	Nuevo Laredo	35.98
Kapoeta	31.09	Pasamonte	33.94
Molteno	32.09	Serra de Magé	29.42
		Sioux County	33.30
		Stannern	33.93
<u>Table 4.4</u>			
Mincy	14.66		
Patwar	25.77	<u>Table 4.8</u>	
Estherville	23.96	Binda	31.17
Mount Padbury	15.78	Bununu	30.35
Vaca Muerta	27.53	Chaves	32.00
Emery	14.45	Frankfort (F)	31.52
Łowicz	13.90	Frankfort (T)	31.95
		Malvern	34.88
		Malvern	33.97
		Yamato 7308	28.17
		Zmenj	32.93
<u>Table 4.6</u>			
Vaca Muerta	27.75		
Łowicz	13.89		
<u>Table 4.7</u>			
Allan Hills 7605	31.12	<u>Table 4.9</u>	
Béréba	34.69	Ellemeet	30.58
Cachari	32.21	Johnstown	32.52
Haraiya	32.48	Shalka	29.42
Juvinas	33.67	Tatahouine	30.52
Lakangaon	37.78	Yamato 6902	24.43
Macibini	33.91	Barea	23.51
		Dyarri Island	30.55

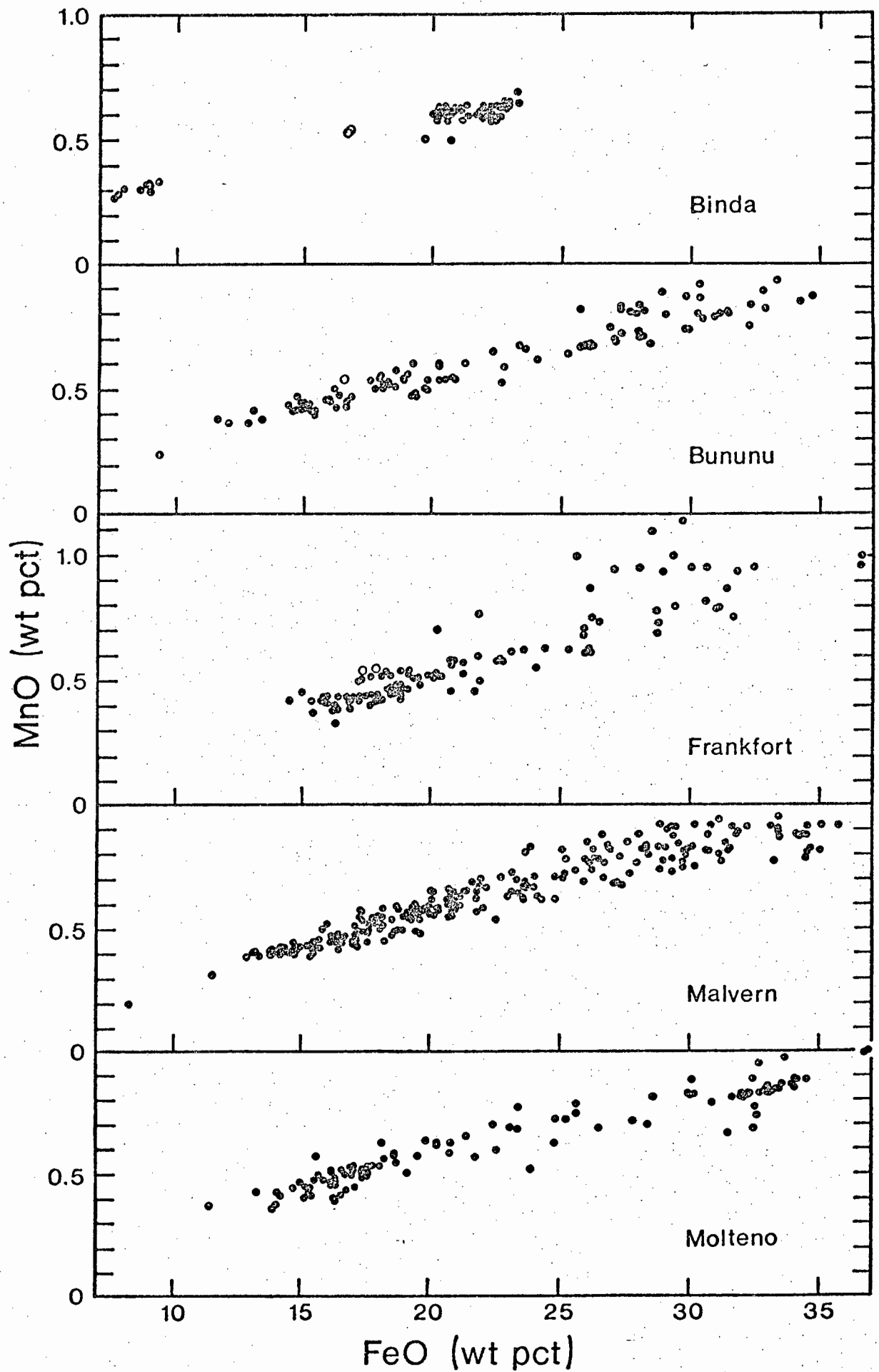
Table 7.2. FeO/MnO (wt) ratios in the pyroxenes of the five meteorites analyzed by electron microprobe

METEORITE	FeO/MnO (wt) in pyroxenes		
	Ave.	S.D.	Range
Binda	34.57	3.49	25.65-42.22
Bununu	36.40	2.87	30.56-42.80
Frankfort	37.64	4.38	25.47-47.79
Malvern (cpx)	36.12	3.22	28.39-44.15
Malvern (opx)	34.59	2.33	29.76-41.74
Malvern (all px)	35.38	2.79	28.39-44.15
Molteno	35.85	3.71	27.47-47.72

S.D. - standard deviation

present in the pyroxene ratios in all five meteorites further justifies the withdrawal by HEWINS (1979b) noted above. However, plotting of the ratio (Fig. 7.22) shows that it remains constant with increase in FeO. This appears to be true even of the Binda pyroxenes. In contrast to the continuity of the other four trends depicted, their trend is discontinuous, being divided into low- and high-Ca groups, but the line on which these groups plot has the same slope as the achondritic pyroxene trends. The trend is not sufficiently extensive to show whether the FeO/MnO ratio decreases with increasing FeO, as noted in the pyroxenes of some mesosiderites by HEWINS (1979b, 1981). The pyroxenes of Dyarri Island do not, however, show this decrease to any marked degree, but define a trend of slope similar to that of achondritic pyroxenes, as does Binda. It is possible, therefore, that the achondritic affinities of these two meteorites (sections 5.3.2 and 5.3.3) are reflected in the FeO/MnO relationships in their pyroxenes.

Fig. 7.22. FeO-MnO relationships in the pyroxenes of the five meteorites studied. A clear coherence between the concentrations of these oxides is present in all five, although the Frankfort trend shows more scatter than the others at higher concentrations. All the pyroxenes, including those of Binda that define a discontinuous trend, plot on lines of identical slope ($\text{FeO/MnO} = 35$). The bulk ratios for Binda, Bununu, and Frankfort are denoted by hollow circles and plot slightly above the pyroxene trend lines. The bulk ratios for Malvern and Molteno could not be shown because they lie exactly on their respective pyroxene trends. Suggested reasons for this difference are discussed in the text.



Some support for this may be found in the bulk FeO/MnO ratios of the achondrites and mesosiderites (Table 7.1). The bulk ratios of the eucrites, howardites, and diogenites, considered as a group, are relatively high and fairly uniform. Four of the five 'main group' mesosiderites have ratios less than half the magnitude of the general achondritic value; Estherville alone is anomalous. In Fig. 5.14, Barea, Binda, and Dyarll Island constitute a trend approximating that of the achondrites; Binda and Dyarll Island have bulk FeO/MnO values similar to those of the achondrites (Table 7.1). Moreover, the mesosiderites Patwar and Vaca Muerta, intermediate in Fig. 5.14, have values of the ratio intermediate between those of the 'main group' mesosiderites and the achondrites. There is thus a general correspondence between the bulk FeO/MnO ratios in mesosiderites and the hypothesis of their progressive oxidation to produce the source material for the main classes of achondrites (sections 5.3.2 and 5.3.3), and this may extend to the behaviour of Fe and Mn in mesosideritic pyroxenes.

In the compilation of Table 7.2, the ortho- and clinopyroxenes in Malvern were initially treated separately in order to test whether variation related to the FeO content of the pyroxenes was present in their FeO/MnO ratios. The average ratio was found to be slightly, but not significantly, higher in the clinopyroxenes, which contain more Fe.

The bulk ratios for Binda, Bununu, and Frankfort plot slightly above the trends established by the pyroxenes in Fig. 7.22 because these ratios are numerically somewhat lower than the pyroxene values (Tables 7.1 and 7.2). Conversely, the bulk values for Malvern and Molteno could not be shown on account of their similarity to the ratios in the pyroxenes. This implies the existence of slight differences in the partitioning of Fe and Mn in the source materials of these meteorites. These differences appear to be related to the bulk content of Mg in the meteorites. The near-correspondence of the bulk and

pyroxene ratios in the less magnesian howardites Malvern and Molteno suggests that most of the available Fe and Mn was partitioned into the pyroxenes (cf. Kapoeta: DYMEK et al., 1976). In the other three meteorites, the FeO/MnO ratios in the pyroxenes may have been raised above the bulk value as a result of competition for Mn by chromite, which may be more abundant in representative samples of these more magnesian meteorites than the sections studied suggest. Alternatively, the presence of magnesian olivine (not found in the present investigation) might account for the slight differences in the ratios.

DYMEK et al. (1976) concluded, from the coherence of FeO and MnO, that the source materials for the howardite Kapoeta were formed in fundamentally related physical-chemical environments different from those of the lunar rocks, and attributed the difference to different initial proportions of oxides and metal in the primordial source materials. The extension of this reasoning to the present study suggests that the materials from which Bununu, Frankfort, Malvern, and Molteno were derived originated in physical-chemical environments similar to one another and to that of Kapoeta. If, as suggested by Dymek and his co-workers, the governing factor in the FeO-MnO relationship is the oxide-metal ratio in the source materials, then the similarity of the bulk FeO/MnO ratios of Binda and Dyarrl Island to those of the achondrites (Table 7.1), and the correspondence of these ratios in their pyroxenes to the achondritic value of 35 (Table 7.2, this work; Fig. 6, HEWINS, 1979b), can both be attributed to the change brought about in their oxide-metal ratios by progressive oxidation of the metal in the mesosideritic source. The sample of Binda studied was, like the howardites, practically devoid of metal. MASON and JAROSEWICH (1973) reported 17.49% metal in Dyarrl Island, and the slight decrease of the FeO/MnO ratio in its pyroxenes with increasing FeO may signify that it has retained more of its mesosideritic character than Binda has. The slightly lower bulk FeO/MnO ratio in Dyarrl Island (Table 7.1) is in accordance with this suggestion.

7.2.7 Chondritic pyroxenes?

In section 3.3.4, it was surmised that a clast consisting of a radiating aggregate of brownish orthopyroxene of unusual appearance in Malvern is part of a chondrule, one of the very few indications of the presence of a chondritic component in howardites revealed by the present study (see Plate 3.9C). The pyroxenes in this aggregate were analyzed by microprobe and were found to be of constant composition, with an average value $Wo_{1.5}En_{72.4}Fs_{26.1}$ (see MAOP2/6, Table A3.26). This composition is plotted in Figs 7.13 and 7.14, and examination of these figures shows that the Wo content is slightly lower than the average for that part of the trend. This, however, is not a unique instance and may therefore be of analytical origin. Furthermore, the pyroxenes of the supposed chondrule are slightly more Fe-rich than the range quoted for the L-chondrites by MASON (1968). The compositional data therefore do not unequivocally confirm the petrographic indications that the orthopyroxene aggregate is of chondritic origin.

7.2.8 Olivines

The compositions of the scarce olivines in Malvern and Molteno are plotted in Figs 7.13 and 7.16 respectively. The compositional range in Malvern is $Fo_{65} - Fo_{44}$, while that in Molteno is much narrower ($Fo_{70} - Fo_{68}$) because all the Molteno olivines occur in a single equilibrated dunite clast. Little can be deduced on the origin of the olivines on account of the small number analyzed. The ranges in both howardites lie well within the total ranges given for the howardites ($Fo_{89} - Fo_{16}$; DESNOYERS and JÉROME, 1973, and DELANEY et al., 1980) and for the mesosiderites ($Fo_{90} - Fo_{55}$; DELANEY et al., 1980). It should be noted, however, that the Malvern range reported here and the total howardite range greatly exceed the compositional range of diogenitic olivine ($Fo_{76} - Fo_{68}$; HEWINS, 1981). This suggests that olivine from other

than diogenitic sources contributed to the howarditic breccias, and strengthens the similar inference that can be drawn from the presence in howardites of orthopyroxenes far more magnesian than those of the diogenites. Observations such as these point to greater complexity in the processes of formation of the howardites than are implicit in the simple eucrite-diogenite mixing model of JÉROME and GOLES (1971).

7.3 THE PHASE CHEMISTRY OF THE OPAQUE MINERALS

7.3.1 Chromites

In his study of the mineralogy and chemistry of nine diogenites, GOOLEY (1972) concluded that the chromites of diogenites could be distinguished from those of eucrites on the basis of the Fe/Mg ratio (see his Fig. 7). He therefore suggested that the difference in this ratio (caused by the chromites having equilibrated with pyroxenes of different compositions) could be used to test the mixing model of JÉROME and GOLES (1971) for the formation of howardites. Accordingly, the analytical data on chromites acquired in the present study (Tables A3.1 - A3.5) were used to evaluate this suggestion, which implies recognizable bimodality in the distribution of Fe/Mg ratios of howarditic chromites if howardites originated from the mixture of diogenites and eucrites.

Table 7.3 summarizes the results of this test. Within the limits of sample size, all five distributions proved to be continuous and without any indications of bimodality. The Bununu distribution showed a concentration of values in the lower part of the range, but this was not matched by a corresponding concentration of high values. The modes of occurrence of the chromites with ratios at the extremities of the ranges were also noted but, because these crystals generally proved to be clasts in the breccia 'matrix', this provided little evidence either for or against the mixing hypothesis.

Table 7.3. Ranges in the Fe/Mg (atomic) ratios in chromites in the five meteorites studied, and the modes of occurrence of the crystals at the extremes of these ranges

METEORITE	Fe/Mg (atomic) in chromites	Mode of occurrence of extremes	
		Lower	Higher
Binda	5.46-12.63	'Lithic'	'Matrix'
Bununu	1.92-14.02	'Matrix'	'Matrix'
Frankfort	4.99- 9.85	'Matrix'	'Matrix'
Malvern	9.65-29.08	Recrystall.diogenite	'Matrix'
Molteno	2.04-12.47	'Matrix'	'Matrix'

Binda, shown by this work to be practically, but not completely, monomict (see sections 7.2.1 and 7.2.3) was included in the test only to establish whether the chromites in the 'lithic' clasts are of the same composition as those in the comminuted 'matrix' material. Surprisingly, a fairly wide range of Fe/Mg ratios was revealed (Table 7.3), with chromites in both modes of occurrence randomly distributed throughout this essentially continuous range. This appears to indicate a lack of equilibrium between the chromites and magnesian pigeonites in Binda, there being no evidence for an exotic origin for the chromites.

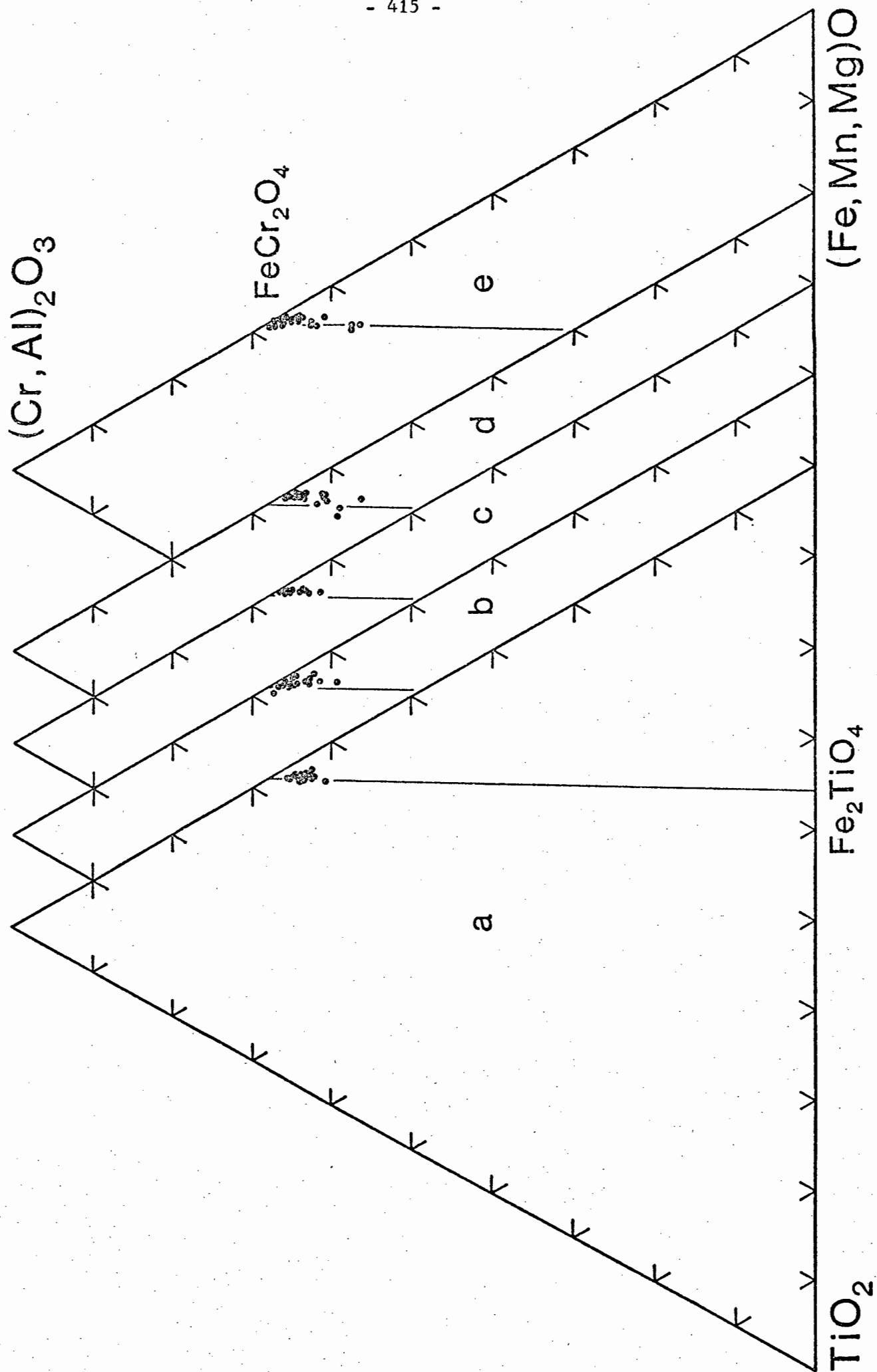
As a further means of studying major element variations in the chromites of the five meteorites, the ternary plot TiO_2 - (Fe,Mg,Mn) - $(\text{Cr,Al})_2\text{O}_3$ used by CAMERON (1971) to compare Apollo 11 and Apollo 12 spinels was adopted (Fig. 7.23). The more complicated projection system proposed by BUSCHE et al. (1972) to represent the compositional complexity of lunar spinels was considered, but inspection of the data (Tables A3.1 - A3.5) showed that its use was not warranted. The plot used in Fig. 7.23 shows clearly whether compositional variation is present in the chromite-ulvöspinel

series. The end-members of this series (essentially FeCr_2O_4 and Fe_2TiO_4 respectively) are joined by a line in each of the plots in Fig. 7.23. These plots show that the spinels in all five meteorites are closely similar to one another on this basis of comparison, and that all are practically pure chromites. Very little substitution of Ti for Cr has taken place, with Binda showing slightly less variation than the four howardites. This constancy of composition in the meteoritic chromites is in sharp contrast to the variability present in the Apollo 11 and Apollo 12 spinels (CAMERON, 1971, Fig. 5) and in those of the Apollo 14 crystalline rocks studied by EL GORESY *et al.* (1972), who employed the same method of presentation of their data. The apparent uniformity of Cr and Ti in the plotted meteoritic chromites contrasts also with the wide and continuous variations in Fe and Mg noted above. The wide range of Fe/Mg values present in these chromites (Table 7.3) suggests derivation from compositionally diverse but related source rocks, as indicated also by studies of pyroxenes and plagioclases earlier in this chapter. The absolute concentrations of Cr and Ti in the chromites (Tables A3.1 - A3.5) point to variability in these elements also in the source rocks, but no simple relationship could be established between them, or between them and the observed Fe-Mg variations.

7.3.2 Ilmenites

Ilmenites were analyzed in Binda, Bununu, Malvern, and Molteno, and are plotted in Fig. 7.24 in Ti-Mg-Fe ternary diagrams. These plots show that little compositional variation is present. In Binda in particular, all the ilmenites plot in virtually the same position, which is slightly removed from that of pure ilmenite because of minor substitution of Mg for Fe (Fig. 7.24a). The points representing ilmenites in Bununu (Fig. 7.24b) and Malvern (Fig. 7.24c) are clustered close to the theoretical position of the pure mineral,

Fig. 7.23. Compositional variations in the chromites of the five meteorites studied in terms of the ternary plot $(\text{Cr,Al})_2\text{O}_3$ - TiO_2 - $(\text{Fe,Mg,Mn})\text{O}$; cf. Fig. 5, CAMERON (1971). Compositions were recalculated to molecular proportions. The joins link the end-members of the chromite-ulvöspinel series. The plots show that the chromites of all five meteorites are similar, and that they contain little of the ulvöspinel component. Binda (a) exhibits slightly less variation than the howardites, in which the variability increases with decreasing Mg content from Frankfort (c) through Bununu (b) and Malvern (d) to Molteno (e).

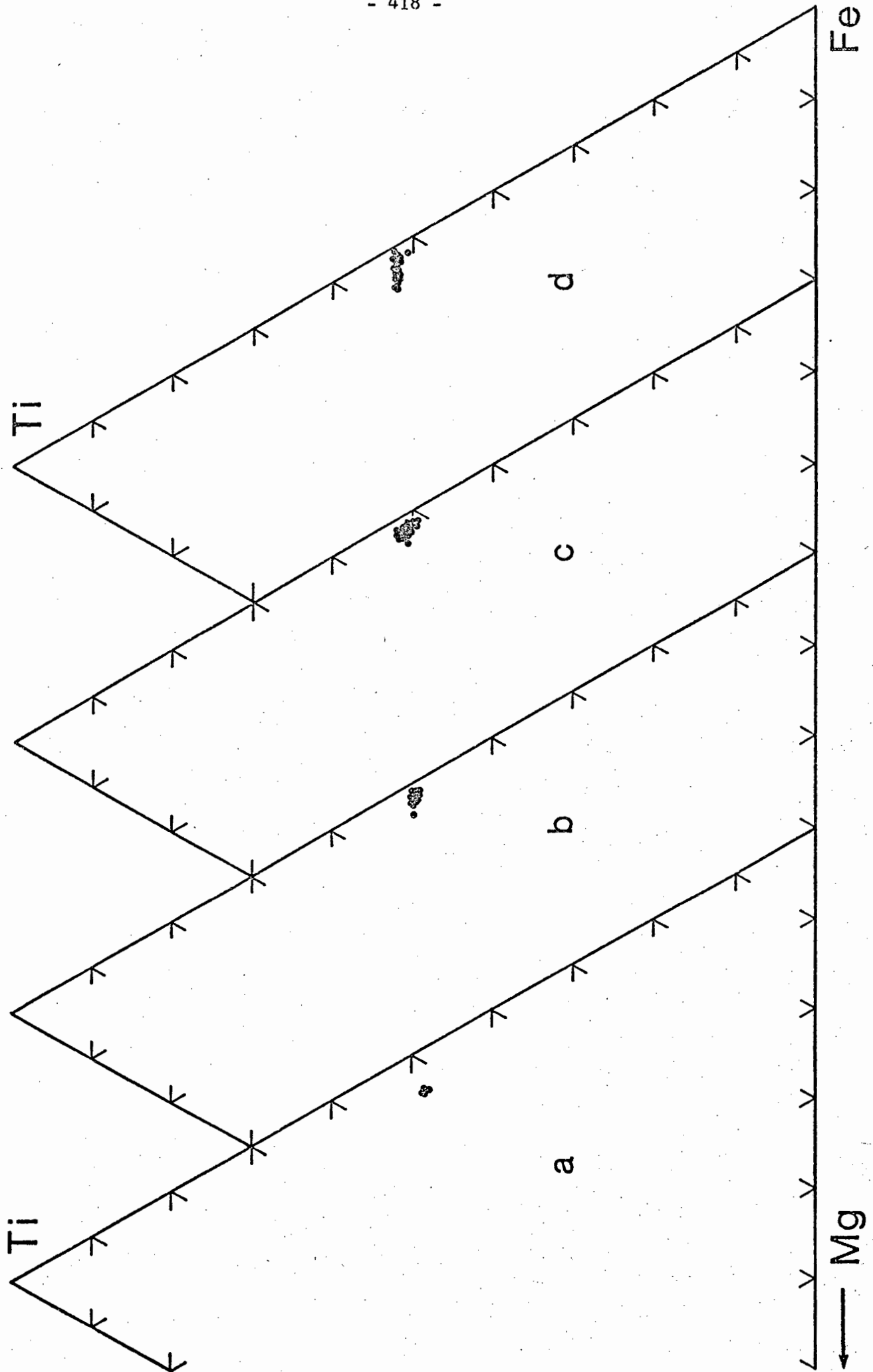


and show only very slight substitution. The Molteno examples (Fig. 7.24d) show a greater degree of Mg substitution, resulting in the plotted points falling on part of the join between ilmenite (FeTiO_3) and geikielite (MgTiO_3). A slight displacement of the points towards the Ti apex is thought to be real, not analytical (see below). Similar substitution of Mg for Fe in the ilmenites of the highlands rocks of the Taurus-Littrow Valley (Apollo 17) was reported by BENCE et al. (1974), but many of the lunar ilmenites contain a higher proportion of the geikielite component than those of Molteno. Conversely, the ilmenites in Apollo 11 samples studied by KEIL et al. (1970) are enriched in Mg to only the same extent as the Molteno ilmenites, and define a trend only slightly different from those of the chondrites and of the achondrites and mesosiderites considered together. These trends, like that of the Molteno ilmenites, show a displacement away from the ilmenite-geikielite join in the direction of Ti-enrichment. The reason for this is not apparent.

7.3.3 Metals

No exhaustive analytical study of the metals was attempted, but basic compositional data were obtained on the sparsely-distributed metal phase in Bununu, Malvern, and Molteno (Tables A3.11 - A3.13), and on the single grain observed in Binda (Table A3.10). The inter-relationships between Ni and Co were plotted for the three howardites (Fig. 7.25). Malvern provided the greatest number of analyses, all of which (except the few taenites) plot in the range 3%-7% Ni. Co values lie between 0.5% and 1.0% in the kamacite phase, but are uniformly low (about 0.2%) in the taenite. The Bununu metals show more scatter, particularly in Co; one grain contains the highest concentration recorded in the three howardites (3.64%). The one taenite analyzed in Bununu has a content of Co almost twice that of its counterparts in both Malvern and Molteno, but at a lower Ni concentration. The metals in

Fig. 7.24. Ilmenite compositions in (a) Binda, (b) Bununu, (c) Malvern, and (d) Molteno plotted in atomic proportions in Ti-Mg-Fe ternary diagrams. The compositions in Bununu and Malvern correspond closely to pure ilmenite, with negligible substitution of Mg for Fe. The ilmenites in Binda are practically identical to one another, and show minor Mg substitution. In Molteno, the mineral shows a small compositional range from pure ilmenite to ilmenite with about 5% of the geikielite component. The trend does not lie along the ilmenite-geikielite join but, as in some Apollo 11 samples (KEIL *et al.*, 1970), is slightly displaced towards the Ti apex of the diagram.



Molteno exhibit the widest range of Ni values - from almost zero to 54.5% - with Co at about the same concentration level as in Malvern; one kamacite in the 'matrix' contains the unusually high amount of 2.17% Co. The exceptionally high concentration of Co in the solitary grain in Binda (10.13%) could not conveniently be represented in Fig. 7.25. This is almost five times the value reported in LOVERING (1964), and the Ni content in the grain is correspondingly high (7.79%; Table 6.3). However, the Ni/Co ratio for this grain (0.77) is similar to the average of Lovering's determinations (0.82).

WLOTZKA et al. (1972) compared the Ni/Co ratios of metallic particles in Apollo 14 and 15 soils with the cosmic value of 20. Fig. 7.25 shows that virtually none of the metal grains analyzed approach the cosmic value; the only possible exceptions are two of the intermediate compositions from Molteno.

GOLDSTEIN and YAKOWITZ (1971) reviewed the then available analytical data on meteoritic metals and showed those present in iron meteorites, pallasites, and chondrites plot in a restricted zone with a slight positive slope in Co-Ni diagrams such as Fig. 7.25 (see their Fig. 1). They plotted the mean compositions of metals from Macibini and Binda (LOVERING, 1964) to characterize the locations of eucritic and howarditic metal respectively, but these may not have been the most felicitous of choices in terms of either composition or classification. EL GORESY et al. (1973) established a broader zone at higher Co concentrations and with a greater slope (their Figs 5 and 6) than that of Goldstein and Yakowitz. This zone, which was based on all analyzed metals from Apollo 12 and Apollo 15 igneous rocks, was claimed to include achondritic compositions also. This observation has an important bearing on discussions on the amount of metal of meteoritic origin present in the lunar soils, and El Goresy and his colleagues stressed the need for more data on the metal phase in achondrites to be included in the Co-Ni

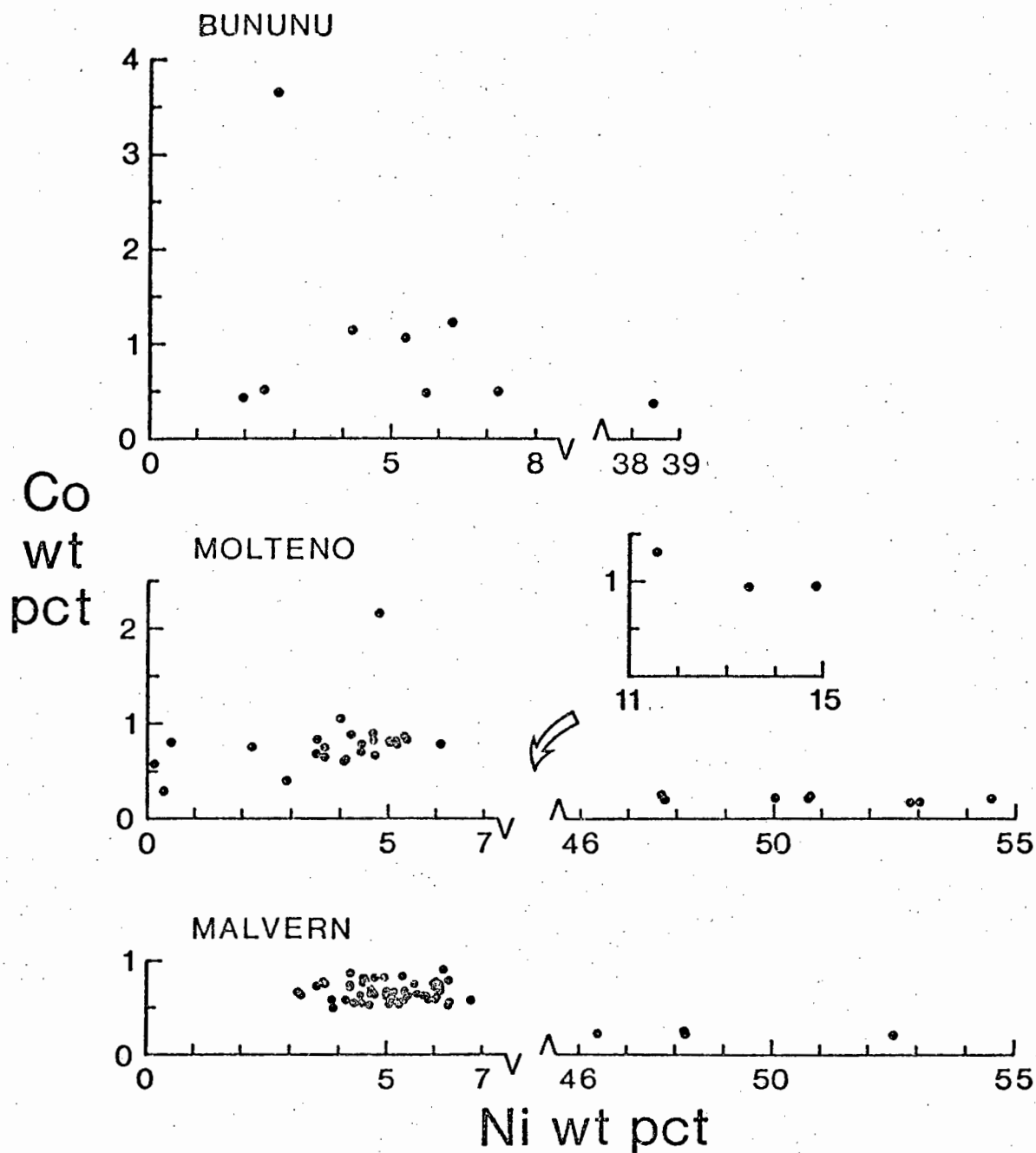


Fig. 7.25. Co-Ni plots of analyzed metals in the howardites Bununu, Malvern, and Molteno. The majority of the analyses are of kamacite, but taenite (in some instances co-existing with the kamacite) is also represented. The lower concentration of Co in taenite is noticeable. Although the distribution of kamacite analyses is less coherent in Bununu than in the other two howardites, all three appear to conform approximately to the upper limit of the meteorite metal zone defined by GOLDSTEIN and YAKOWITZ (1971). Primary metal compositions, i.e. low Ni, low Co (HEWINS and KLEIN, 1978), are clearly evident only in the Molteno plot, but this topic is further discussed in the text.

present investigation produced no analyses of the small and rare metal grains in this mode of occurrence. In another study of metal in Malvern, HEWINS and KLEIN (1978) proposed that primary metal in the achondrites, i.e. metal included in mineral and lithic clasts, is compositionally similar to that in primary lunar anorthositic rocks as established by HEWINS and GOLDSTEIN (1975). These primary compositions are essentially low in Ni, but Co concentrations may be considerably higher than in the zone of meteoritic metal established by GOLDSTEIN and YAKOWITZ (1971); the compositional field of primary metal is shown in the diagrams of HEWINS and KLEIN (1978) and of HEWINS (1979a). The rarity of primary metal in achondrites was recognized by these authors, and the petrographic part of the present study (Chap. 3) confirmed that metal in modes of occurrence that might indicate a primary origin is very rare in the five meteorites investigated. The single grain analyzed in Binda is primary (it is an inclusion in pigeonite) but may not fall in the field of metal compositions in coarse anorthosites (Fig. 10, HEWINS and GOLDSTEIN, 1975) because of its exceptionally high content of Co. Three of the Bununu metals plot in the primary field (Fig. 7.25); that with the highest Co content occurs in the 'matrix' and is therefore of indeterminate origin, but the remaining two are inclusions in the same pyroxene crystal. One metal grain in a lithic clast in Malvern was analyzed, but plots in the zone of meteoritic metals. Two of the three analyses that plot in the primary field in the Molteno diagram are of metals in the 'matrix'; the third, however, is of an inclusion in a pyroxene and is most probably of primary origin.

All four meteorites for which analyses were obtained appear, therefore to contain exceptions to the distribution of primary compositions suggested by HEWINS and KLEIN (1978), but the analyses available are too few to make this a firm conclusion. Moreover, HEWINS (1979a) produced evidence,

particularly from Bununu, to show that some apparently primary metal may have been introduced into lithic clasts and minerals during impact-produced shock. Such metal would be compositionally similar to the impacting projectile's metal, and would plot in the meteoritic metal field, as observed in Malvern. The present investigation and those of HEWINS and KLEIN (1978) and HEWINS (1979a) are, however, in complete agreement on the distribution in achondrites of metal compositions that are not of primary origin, and on the interpretation of that distribution. All of these studies have shown that metals in modes of occurrence that are not clearly primary plot in, or along the upper limit of, the field of meteoritic metal compositions defined by GOLDSTEIN and YAKOWITZ (1971). These metals occur mainly in the glasses and glassy microbreccias (referred to by Hewins and his co-workers as 'melt rocks'), but also in the 'matrix' material of the three howardites under discussion. They are regarded as remnants of impacting high-velocity projectiles that generated the shock effects present in these meteorites and melted a proportion of the comminuted 'matrix' material to produce glasses, and therefore reflect exotic metal compositions with Ni/Co ratios different from those of primary achondritic metals. DESNOYERS and JÉROME (1977) showed from textural evidence that the enclosing glasses cooled too rapidly to effect re-equilibration of the metallic particles. Chemical evidence from the metals included in four glassy microbreccias in Malvern in support of the idea that, in general, re-equilibration of these metals did not take place is set out in Table 7.4. Wide ranges are present in the Ni concentrations and also, in relative terms, in the Co. The compositional variability of the metal inclusions points to projectiles of varying compositions having impacted on the surface of the howardite parent body (or bodies) and having contributed fragments both to the impact glasses and to the comminuted ('matrix') materials of the surface deposits, where their subsequent incorporation in glasses produced by later impacts may also have taken place.

Table 7.4. Average concentrations of Ni and Co in metals included in four glassy microbreccias in Malvern, and the concentration ranges of these elements present in the metals

Glassy microbreccia	Ni (wt%)	S.D.	Co (wt%)	S.D.	No. in ave.*	Ranges (wt%)
MAMBR2/04	5.30	0.69	0.71	0.11	4	Ni: 4.49-6.11 Co: 0.55-0.76
MAMBR2/07	5.40	0.49	0.59	0.04	6	Ni: 4.97-6.03 Co: 0.53-0.64
MAMBR2/08	4.86	0.84	0.61	0.05	16	Ni: 3.18-6.31 Co: 0.53-0.68
---	6.23	0.09	0.61	0.10	3	Ni: 6.16-6.29 Co: 0.54-0.68

S.D. - standard deviation

* - most of the compositions used to calculate the averages in this table are themselves averages taken from Table A3.12.

HEWINS and KLEIN (1978) observed that the compositions of metals included in glassy materials in Malvern tend to cluster about 4% and 6% Ni within the meteoritic metal field. The same tendency was noted, but in lesser degree, in the metals of the 'matrix' of Malvern. The data of the present study do not show this bimodality (see Fig. 7.25 and, for instance, the ranges in Table 7.4) either in Malvern or in the other two howardites. The concept was not stressed by HEWINS (1979a), presumably because of the absence of similar clustering in other howardites examined, e.g. Kapoeta.

7.3.4 Troilites

Troilites were analyzed in only Malvern and Molteno (Table 6.7). In many occurrences in these and the other meteorites, the mineral is present in too finely-divided a form for analysis. As noted in Chap. 6, the data for Malvern are slightly more variable than those of the Molteno troilites. Little substitution of Ni and Co for Fe is evident in the Malvern examples, in which these elements were determined. The better analyses of Malvern troilites, and all of those from Molteno, indicate that the compositions of these sulphides are stoichiometric, as is generally the case in meteoritic troilites.

7.3.5 The distribution of P in Malvern

The petrographic examination of Malvern (section 3.3.2) did not disclose the presence of any P-bearing phases that might account for the small amounts of P_2O_5 (0.059% and 0.072% respectively) in the two new analyses of Malvern (Table 4.2). This was in keeping with the experience of previous investigators; DUKE and SILVER (1967) and FUCHS (1969) did not observe P-bearing minerals in either howardites or eucrites. However, DYMEK et al. (1976) discovered (and analyzed) the phosphates whitlockite and fluor-apatite in basaltic clasts in Kapoeta. An attempt was therefore made during the microprobe examination of Malvern to locate the P-bearing phases that had evaded detection by optical techniques. This was not intended to be a comprehensive study of the distribution of the element, even in the one howardite, but the results proved interesting, allowing for the semi-quantitative approach adopted, and are summarized below.

P has four different modes of occurrence in Malvern:

- (i) It occurs as a constituent of all the glassy materials of which this meteorite has an unusually high content. These materials, which in Malvern

were subdivided into 'true' glasses, the glasses of the matrices of the glassy microbreccias, and devitrified varieties, are regarded as the products of impact-induced melting of regolith material. As such, they might be expected to contain P in proportions similar to that of bulk samples of the meteorite, assuming they were generated in the same source area as that represented by the meteorite breccia. This assumption is open to question, particularly in the 'true' glasses, which in many instances have shapes indicative of flight and therefore transport for an indeterminate distance from their point of origin. Moreover, the possibility of bias in the mixture of regolith materials that was melted to produce the various glassy bodies is ever present. It is perhaps surprising, therefore, to find that the concentrations of a minor constituent such as P show fairly little variation in all three types of glassy material in Malvern, and that they tend to approximate the concentration in the bulk howardite (Table 7.5). No significant differences were observed in the P contents of the three categories of glasses; other compositional differences are discussed in the final section of this chapter.

(ii) Minute fragments of a mineral, almost impossible to analyze but apparently containing up to 43% P_2O_5 , are scattered throughout the comminuted 'matrix' of the meteorite. Their content of P suggests that they are phosphates (apatite or whitlockite).

(iii) A similar fine-grained phase (or phases) occurs in minor amount in lithic clasts of 'basaltic' appearance. In this mode of occurrence these presumed phosphates are generally, but not exclusively, associated with finely-disseminated troilite. Minute inclusions of a phosphate mineral were detected also in some of the rare, very fine-grained clasts of microbreccia that, by analogy with the large clast studied by DESNOYERS and JÉROME (1977), may be of eucritic composition.

Table 7.5. Typical averaged concentrations of P_2O_5 in the three types of glassy material present in Malvern

'True' glasses		Glassy micro-breccias (matrix)		Devitrified glasses	
Sample name	P_2O_5 (wt%)	Sample name	P_2O_5 (wt%)	Sample name	P_2O_5 (wt%)
MAGF1/02	0.041	MAMBR1/01	0.038	MALF1/02	0.273
MAGF1/04	0.062	MAMBR1/03	0.072	MALF1/03	0.068
MAGF1/12	0.058	MAMBR1/05	0.051	MALF1/09	0.072
MAGF1/16	0.023	MAMBR1/06	0.048	MALF1/10	0.065
MAGF1/21	0.173	MAMBR1/07	0.049		
MAGF1/22	0.069				

(iv) A phase rich in P occurs as inclusions in some of the metal grains. The concentration of P_2O_5 in these inclusions does not exceed 36%, suggesting that they consist of schreibersite. Their contribution to the total content of P in Malvern is very small.

7.4 THE CHEMICAL COMPOSITIONS OF THE GLASSY MATERIALS

7.4.1 Introduction

Representative chemical and normative data on the glassy materials present, in greater or lesser amounts, in all five meteorites considered in this chapter are set out in Tables 6.8 - 6.11. The complete (averaged) analytical data (Tables A3.33 - A3.41) are used in this section to study the inter-element relationships of the five most important elements - Si, Al, Fe, Mg, and Ca - in these glassy materials. Recalculation and plotting of the data on ternary diagrams achieves this objective and facilitates comparison with the bulk compositional data on the host meteorites and the inter-element

relationships in the achondrites and mesosiderites included in this study (section 5.9). Such comparison is intended to provide information on the compositional variability of the sources from which the glasses were formed and also on the formational processes.

It is generally accepted that, by analogy with the processes of formation inferred for lunar glasses, meteoritic glassy materials were produced by impact-melting of portions of regolith deposits blanketing the surface of the parent body/bodies. The view has been widely held that such impact melts approximate the bulk composition of the meteorite in which they occur because of their origin by fusion of the same finely-comminuted regolith materials that ultimately underwent lithification and ejection from the parent body to become the meteorite breccia as we now know it. The closeness of the approximation is obviously dependent on whether the fusion was complete or only partial. NOONAN (1974) and NOONAN et al. (1974) observed that glasses in Bununu, Malvern, and Kapoeta show a compositional spread extending into eucrite-like compositions because of enrichment in Ca and Al relative to the bulk compositions of the host howardites. SIMPSON (1974) independently recorded the same observation on the glassy materials in Malvern, and later (1975) noted that the matrix material of the glassy microbreccias most closely resembles the bulk meteorite in a Ca-Mg-Fe ternary plot, with the 'true' glasses and devitrified varieties plotting progressively closer to the position of 'average eucrite' (McCARTHY et al., 1972). Normative plots of the analytical data on glassy materials obtained in the present investigation (Figs 6.1 - 6.6) also indicate compositional differences between these materials and the host meteorites. One of the aims of this part of the investigation is, therefore, to establish the relationships between the various glasses and the corresponding bulk meteorites, and to interpret these relationships in terms of the formational history of the glasses.

The approach adopted is mainly graphical, followed by comparison with the corresponding plots of bulk meteorite data presented in Chap. 5. All such comparisons were made easy for the writer by the availability of the original diagrams drawn to a common scale on transparent materials; the reader, unfortunately, does not share this advantage. The sequence followed is that of section 5.9. It must be emphasized that the term 'glassy microbreccia' refers throughout, as previously, to the glassy matrix material of the clasts, not their total composition.

7.4.2 The Ca-Mg-Fe relationship

The plots of this relationship are shown in Figs 7.26 - 7.28, and should be compared with Fig. 5.28. To facilitate comparison, however, the appropriate bulk composition(s) are plotted in all the figures in this section.

Binda

Binda contains only glassy microbreccias, and these plot in a short trend lying along a line of constant Fe (approximately 30 atomic %) and incorporating the points representing the bulk compositions (Fig. 7.27). This trend diverges slightly but significantly from the achondrite trend depicted in Fig. 5.28.

Bununu

The glasses and glassy microbreccias in Bununu plot along the achondrite trend (Fig. 7.26). All but one of the compositions plotted are richer in Ca and Fe than the bulk meteorite. Some of the microbreccias extend the trend beyond the position occupied by the eucrites in Fig. 5.28, and these points show some scatter.

Frankfort

The single glassy microbreccia analyzed in this howardite plots on the achondrite trend at higher levels of Ca and Fe than both bulk analyses (Fig. 7.27).

Malvern

The glasses in Malvern plot mainly in a tight concentration close to the bulk compositions but at slightly higher values of Ca and Fe (Fig. 7.26). Outlying points elongate the field into a short trend lying at a small angle to the achondrite trend, but this may have no significance. Devitrified glasses plot in a scattered distribution that contains points substantially richer in Ca than the eucrites. The Malvern glassy microbreccias (Fig. 7.28) define a small field whose longer axis coincides with the achondrite trend; the bulk compositions plot in the middle of the field, which is slightly offset towards the Fe vertex of the diagram. A few scattered points extend the distribution into the eucrite field of Fig. 5.28, but the great majority of the analyses fall close to the composition of the host meteorite.

Molteno

The distribution of the glasses (including devitrified varieties) in Molteno shows some scatter but follows the general direction of the achondrite trend to compositions more Ca-rich than the eucrites (Fig. 7.27). All but three of the analyzed glasses plot closer to the Ca-Fe side of the ternary than the bulk composition. This is true also of the glassy microbreccias (Fig. 7.28), which have a compositional range similar to that of their counterparts in Malvern but displaced from the composition of the host meteorite. Analyses that plot in the eucrite field show the scatter noted in the two preceding figures.

Fig. 7.26. The Ca-Mg-Fe relationship in glassy materials in Bununu and Malvern. The compositions of the bulk meteorites are plotted for comparison. The Bununu glasses and some of the glassy microbreccias follow the achondrite trend established in Fig. 5.28. The remaining microbreccias are scattered through, and slightly beyond, the eucrite field. The bulk composition lies at the Mg-rich end of the distribution. The Malvern glasses are fairly tightly clustered in a field that is slightly richer in Ca and Fe than the bulk analyses. Devitrified varieties are compositionally more variable. The points 'M' and 'C' represent the compositions of the glassy matrix and the glassy interiors of skeletal phenocrysts in the unusual clast depicted in Plate 3.4 E. Compositions in this and all other plots in this section are recalculated to atomic percent.

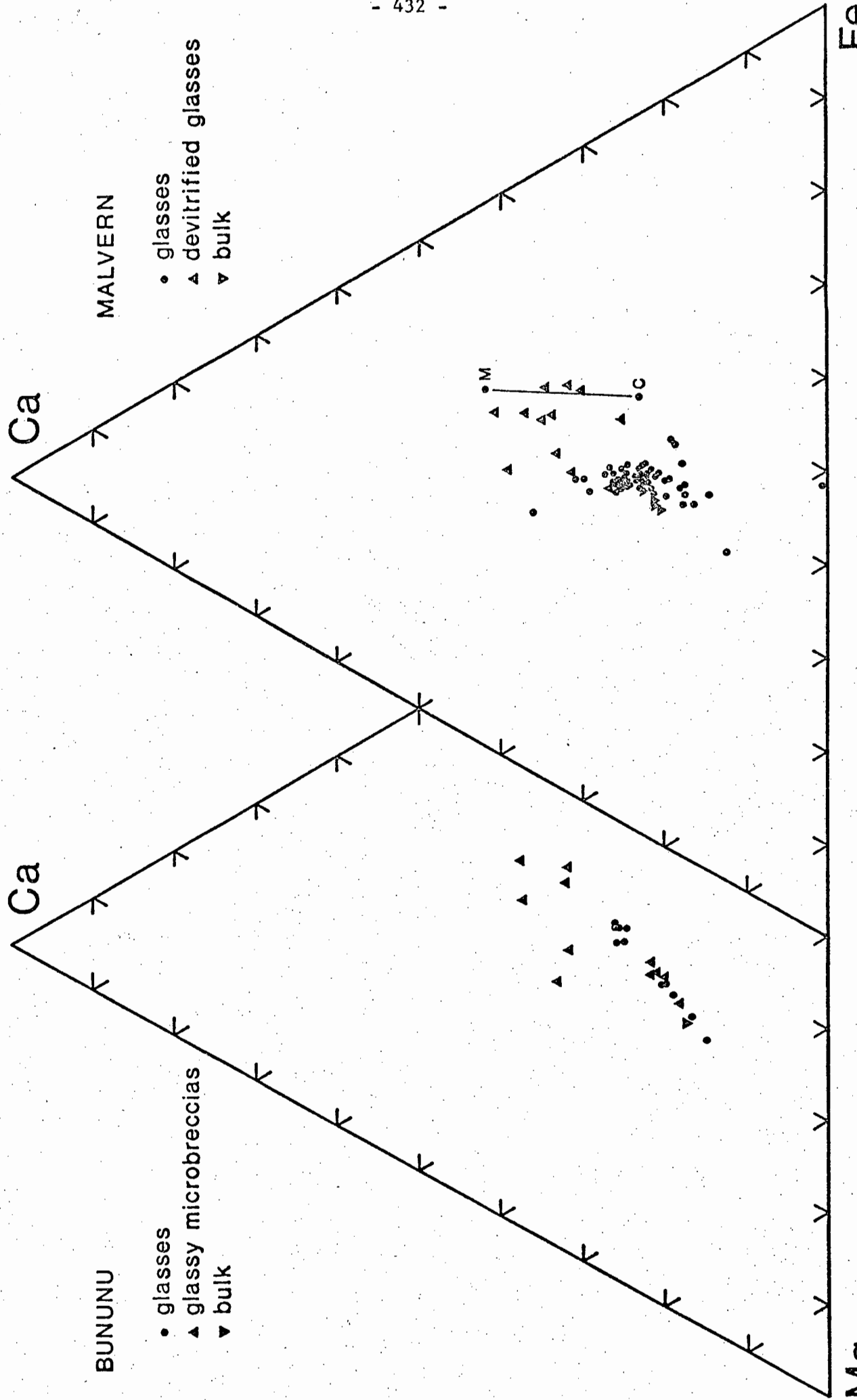


Fig. 7.27. The Ca-Mg-Fe relationship in glassy materials in Binda, Frankfort, and Molteno. Glassy microbreccias in Binda form a well-defined trend (in which the bulk analyses plot) of approximately constant Fe. The only glassy constituent in Frankfort is a microbreccia richer in Ca than the host meteorite. Glasses in Molteno plot in a rather scattered fashion along and beyond the achondrite trend, and practically all contain more Ca and Fe than the bulk analysis.

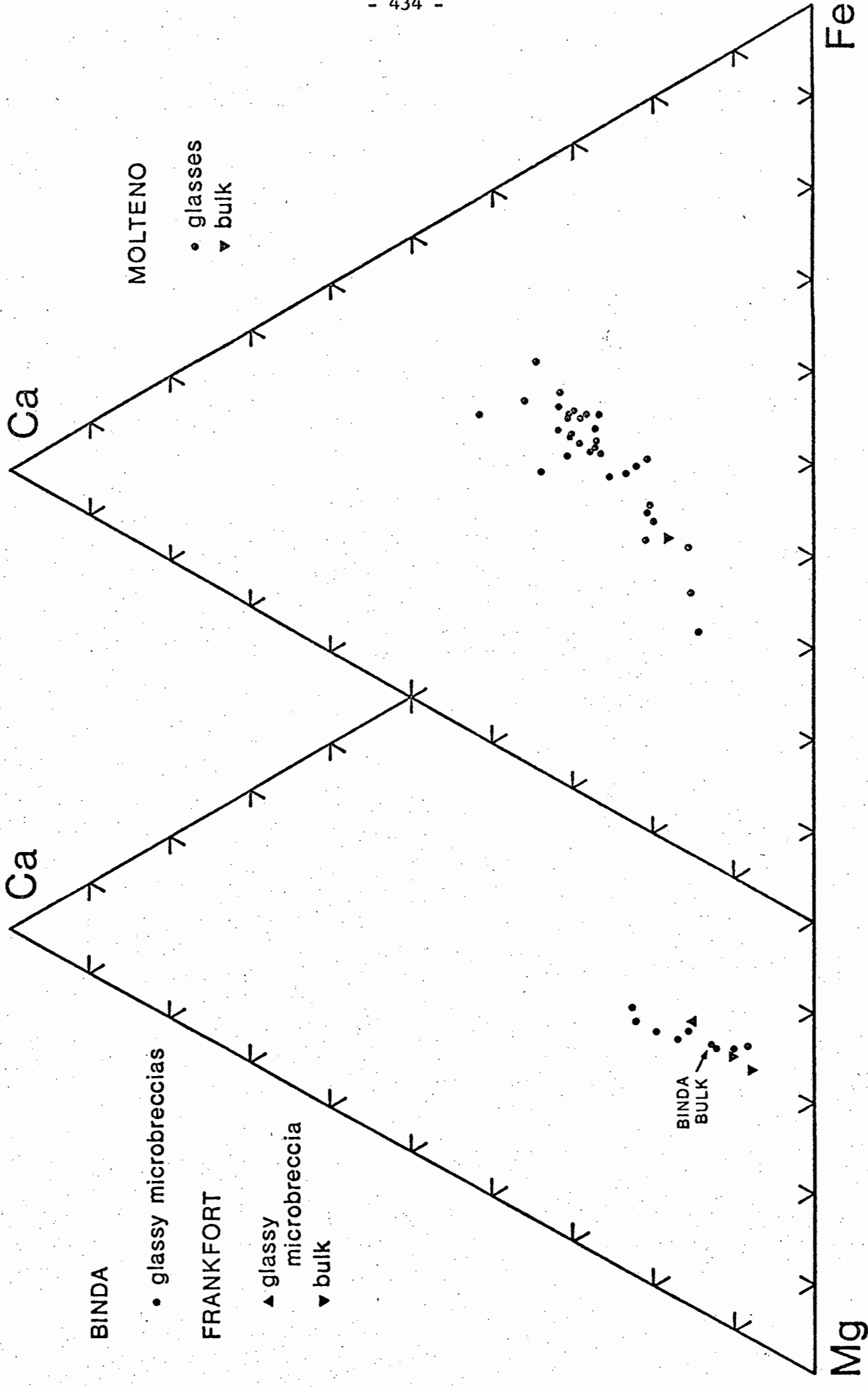
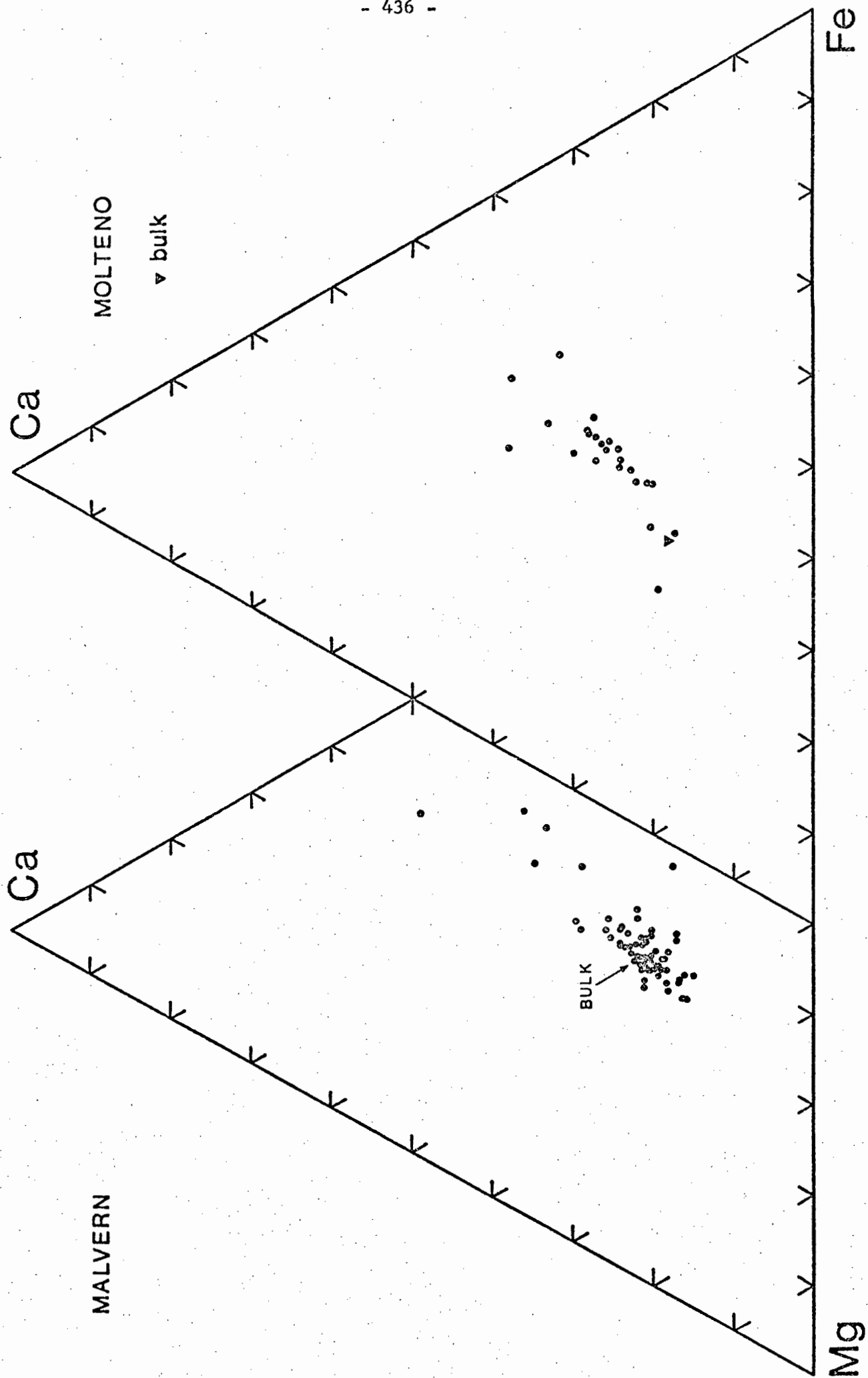


Fig. 7.28. The Ca-Mg-Fe relationship in glassy microbreccias in Malvern and Molteno. Those in Malvern are concentrated close to the bulk analyses of the host, though with a slight tendency towards Fe enrichment. The longer axis of their distribution lies approximately on the achondrite trend. The glassy microbreccias in Molteno show a distribution similar to that of the glasses (Fig. 7.27), with similar enrichment in Ca and Fe relative to the bulk composition of the meteorite.



The plots of the Ca-Mg-Fe relationships show that, in general, a high degree of compositional variation exists in the glassy materials in the five meteorites studied. The variations are systematic and are greater than can be accounted for by sampling or analytical uncertainties (see Table A8.4). The salient generalisation to be drawn from Figs 7.26 - 7.28 is that the compositions of the glassy materials are displaced from the compositions of the host breccias along the trend established for the achondrites in Fig. 5.28 in the direction of increasing Ca. Some clustering around the bulk composition is evident in the glasses and glassy microbreccias in Malvern, but only in Malvern. Considerable variation is present in some of the glassy microbreccias and in devitrified glasses that plot in and beyond the eucrite field. The variation observed in the glassy microbreccias in Binda appears to be of a special type, unrelated to the achondrite trend. The applicability of these observations to other relationships will be tested in the following sections, and an attempt will be made to establish their cause.

7.4.3 The Ca-Mg-Al relationship

It is obvious that in this relationship (Figs 7.29 and 7.30), in source materials lacking highly calcic and aluminous pyroxenes, plagioclase dominates the pattern of variation.

Binda

The glassy microbreccias in Binda (Fig. 7.29) define a linear trend that includes the two bulk analyses, but diverges slightly from the well-marked achondrite trend of Fig. 5.29c towards the Al apex of the diagram.

Bununu

The glasses in Bununu show variation but coincide exactly with the achondrite trend (Fig. 7.29). The majority are significantly enriched in Ca and Al relative to the bulk composition. Some of the glassy microbreccias

lie on the achondrite trend, while others plot around the trend in the vicinity of the eucrite field of Fig. 5.29c. They do not, however, extend beyond the eucrites. Without exception, they plot closer to the Ca-Al side of the diagram than the point representing the bulk analysis of Bununu.

Frankfort

The sole glassy microbreccia in Frankfort falls on the achondrite line, and is richer in Ca and Al than either Frankfort (F) or Frankfort (T) (Fig. 7.29).

Malvern

The distribution of the 'true' and devitrified glasses in Malvern is shown in Fig. 7.30a. The trend of variation in the former coincides approximately with the achondrite trend, with most of the plotted points falling closer to the Ca-Al side of the ternary than at least three of the four bulk analyses. The trend of the devitrified glasses departs from that of the achondrites, however, in the direction of lesser enrichment in Ca, and all of these materials contain more of the plagioclase component than do the bulk analyses. The glassy microbreccias (Fig. 7.30b) exhibit variation along the achondrite trend, but mostly plot in a limited field with the bulk analyses at about the mid-point of its longer axis.

Molteno

The combined variation in the glasses and glassy microbreccias of Molteno produces a trend coincident with that of the howardites and eucrites in Fig. 5.29c and covering the complete compositional range except for the most magnesian howardites (Fig. 7.29). As noted in Chap. 3, distinction between the glasses and glassy microbreccias in Molteno is particularly difficult, and many transitional types exist. This is well illustrated in this plot, in which both extend over similar compositional ranges. All but four of the plotted analyses are richer in Ca and Al than the similarly recalculated host meteorite.

Fig. 7.29. The Ca-Mg-Al relationship in glassy materials in Binda, Bununu, Frankfort, and Molteno. Bulk analyses included for comparison are, as in the figures preceding, denoted by inverted solid triangles unless otherwise indicated. The Binda glassy microbreccias show a fairly high degree of variation, mainly on the high Ca-Al side of the bulk analyses, and the trend does not coincide exactly with the achondrite line of Fig. 5.29c. Frankfort's microbreccia shows similar enrichment in Ca and Al relative to the host composition, as do virtually all the glassy materials in Bununu and Molteno also. The distribution of the analyses in the three howardites conforms to the achondrite trend, with some scatter in the vicinity of the eucrite field.

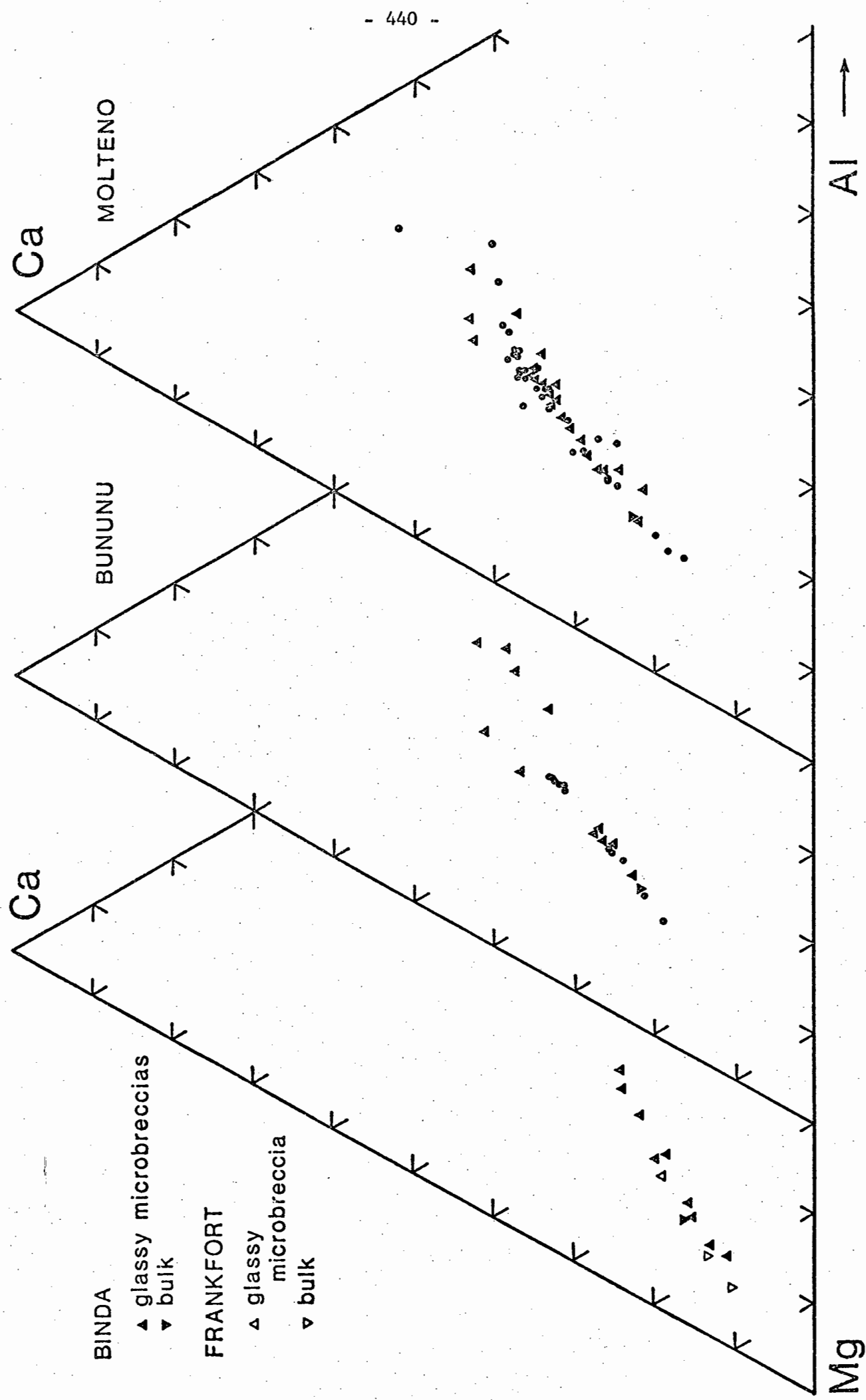
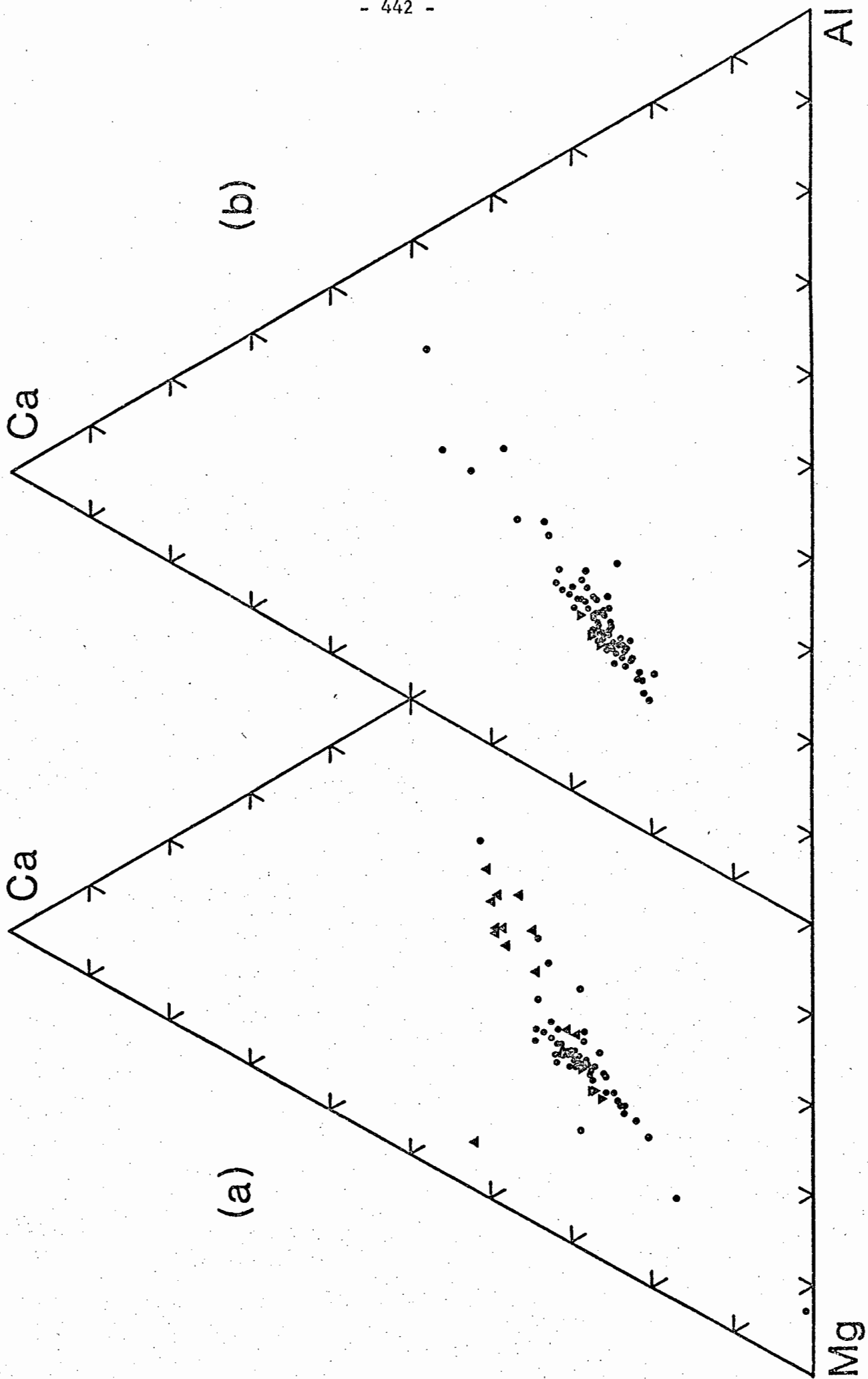


Fig. 7.30. The Ca-Mg-Al relationship in glassy materials in Malvern.

In (a), 'true' glasses (dots) define a small, elongate field on the achondrite trend that includes the four bulk analyses (inverted triangles). Devitrified glasses (upright triangles) plot on a trend slightly divergent from that of the achondrites; these are all richer in Ca and Al than the host meteorite. The distribution of the glassy microbreccias (b) is similar to that of the 'true' glasses in this plot. The analyses mostly cluster around the bulk analyses, but a few extend the trend to high proportions of Ca and Al.



7.4.4 The Ca-Fe-Al relationship

Binda

The glassy microbreccias in Binda plot on a linear trend similar in direction to the achondrite trend in Fig. 5.29b, but slightly displaced towards the Al apex of the diagram (Fig. 7.31a). As noted previously, most of the points plot on the Ca-Al side of the bulk analyses.

Bununu

The distribution of glassy materials in Bununu is fairly condensed in this plot (Fig. 7.31b), occupying mainly that part of the achondrite trend in which the more calcic howardites and some of the eucrites lie. The glassy microbreccias overlap the glasses, but show considerable scatter in the part of the distribution that extends beyond the eucrite field. Most of the glassy materials are richer in Ca and Al than the bulk composition of Bununu.

Frankfort

The glassy microbreccia in Frankfort plots slightly off the achondrite trend in the direction of the Al apex, and is richer in plagioclase components than the two bulk analyses of the host (Fig. 7.31a).

Malvern

The majority of the 'true' glasses in Malvern are concentrated in the same part of the achondrite range as those of Bununu, but the trend does extend into more Fe-rich compositions than in Bununu (Fig. 7.32a). As noted in other plots, there is a slight displacement of the trend towards Al. The four Malvern bulk analyses fall within the main cluster of points. Devitrified glasses plot in and beyond the eucrite field, and all are enriched in Ca and Al relative to the bulk analyses (Fig. 7.32b). The Malvern glassy microbreccias (Fig. 7.32c) show a condensed distribution and a slight displacement from the achondrite trend very similar to those of the 'true' glasses.

Fig. 7.31. The Ca-Fe-Al relationship in glassy materials in Binda, Bununu, Frankfort, and Molteno. Glassy microbreccias in Binda (a) show a fairly wide range of compositions displaced from the achondrite trend towards the Al apex of the diagram. Bununu glasses and some of the glassy microbreccias (b) are condensed into part of the achondrite range of Fig. 5.29b; the remainder are scattered in and beyond the eucrite field. The glassy microbreccia in Frankfort (a) shows the displacements noted in other diagrams that indicate enrichment in Si and Al relative to the bulk meteorite. Molteno glasses (circles) and glassy microbreccias (triangles) show similar enrichments but plot (c) on the achondrite line.

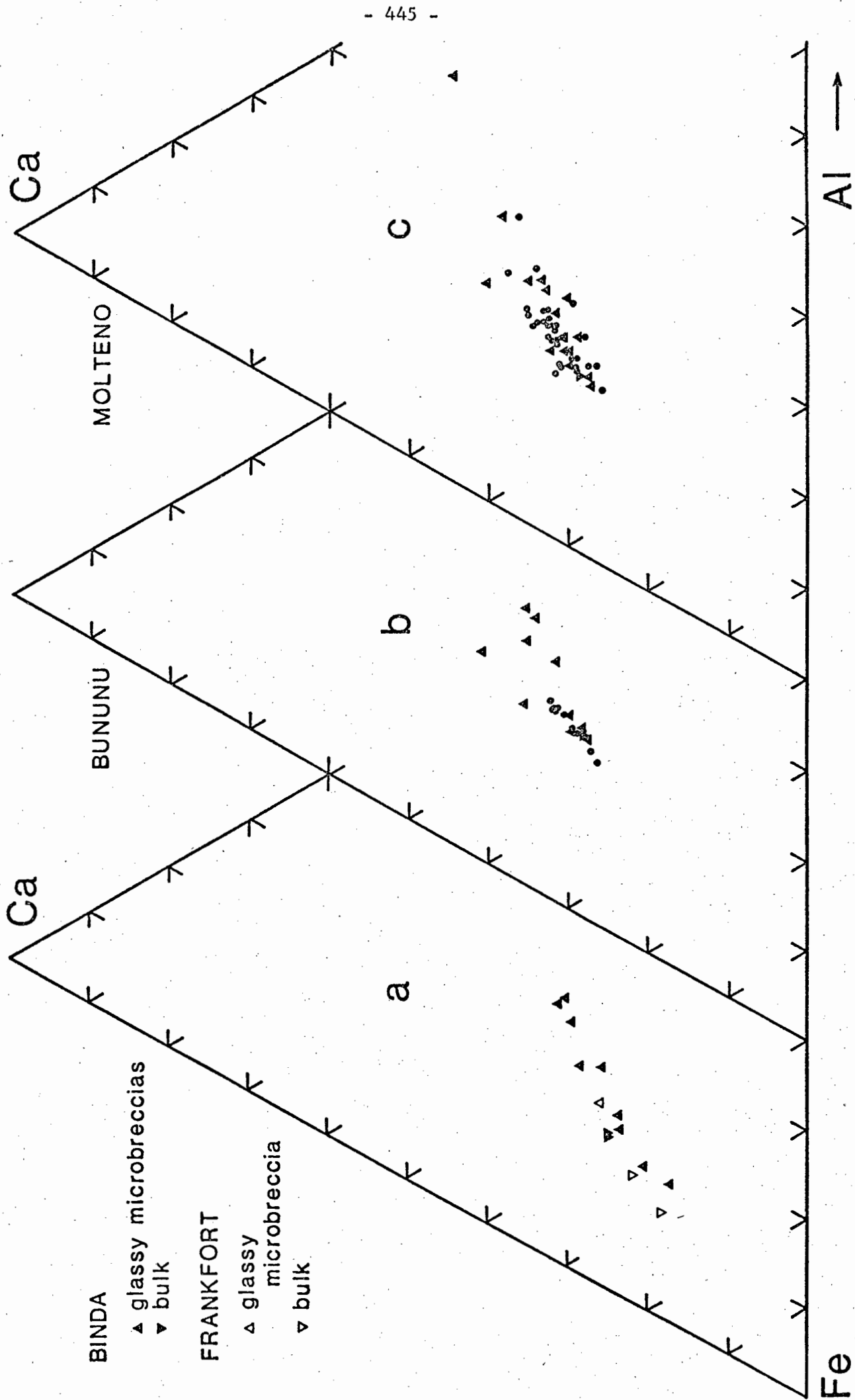
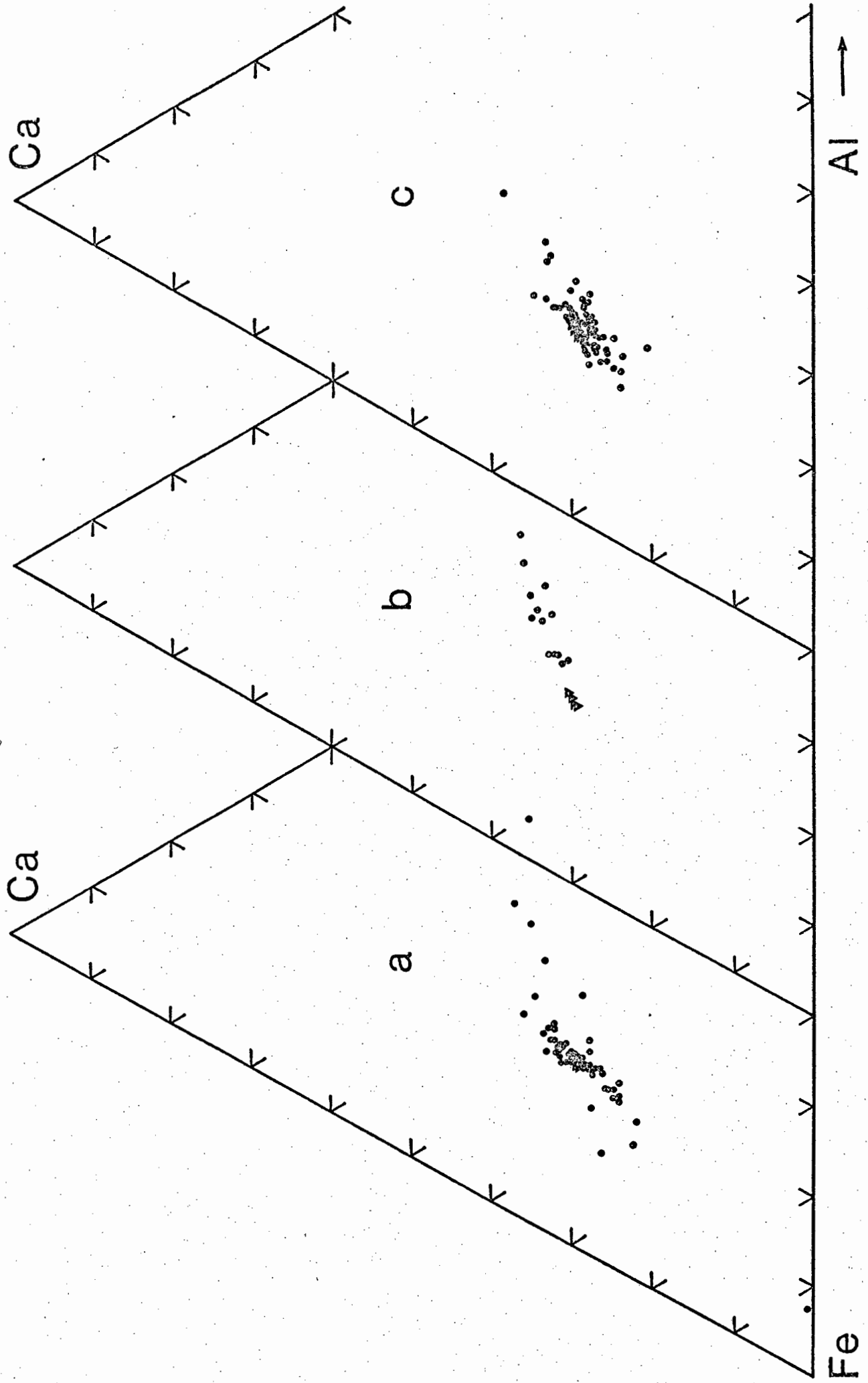


Fig. 7.32. The Ca-Fe-Al relationship in glassy materials in Malvern. 'True' glasses (a) and glassy microbreccias (c) cluster close to the bulk analyses but are slightly displaced from the achondrite line, indicating enrichment in Al. The devitrified glasses (b) contain higher proportions of Ca and Al than the bulk meteorite.



Molteno

The glassy materials in Molteno show concentration and overlap as noted in the plots discussed above, but they plot on the achondrite trend and extend the trend beyond the eucrite field (Fig. 7.32c). All but three of the points lie closer to the Ca-Al side of the diagram than the bulk analysis of the meteorite.

7.4.5 The Ca-Si-Al relationship

Binda

The trend defined by the Binda glassy microbreccia in this plot covers the complete concentration range of the howardites and eucrites established in Fig. 5.29a, but diverges very slightly towards the Al apex as previously noted (Fig. 7.33a).

Bununu

The distribution of glasses in Bununu is very limited, similar to that of Fig. 7.31b in range. Most of the points show enrichment in Ca and Al relative to the host composition (Fig. 7.33b). They coincide with the achondrite trend of Fig. 5.29a, as do the glassy microbreccias (Fig. 7.33c). These, however, extend beyond the eucrite field and are all closer to the Ca-Al side of the diagram than is the Bununu bulk analysis.

Frankfort

The glassy microbreccia in Frankfort also plots on the achondrite trend and is richer in Ca and Al than the bulk analyses (Fig. 7.33c).

Malvern

Clustering around the points representing the bulk analyses of this meteorite is evident in the distributions both of 'true' glasses (Fig. 7.34a) and glassy microbreccias (Fig. 7.34b). These distributions lie on the achondrite trend. The devitrified glasses also show a restricted compositional range that lies in and beyond the eucrite field, on the extension of

Fig. 7.33. The Ca-Si-Al relationship in glassy materials in Binda, Bununu, and Frankfort. The variation in the glassy microbreccias in Binda (a) is almost as wide as in the howardite-eucrite part of the trend in Fig. 5.29a, but the Binda trend swings slightly towards the Al vertex of the ternary plot. Bununu glasses (b) and glassy microbreccias (c) show relative enrichment in Si and Al, but to different degrees. The Frankfort glassy microbreccia (open upright triangle in c) shows similar enrichment by comparison with the two bulk analyses.

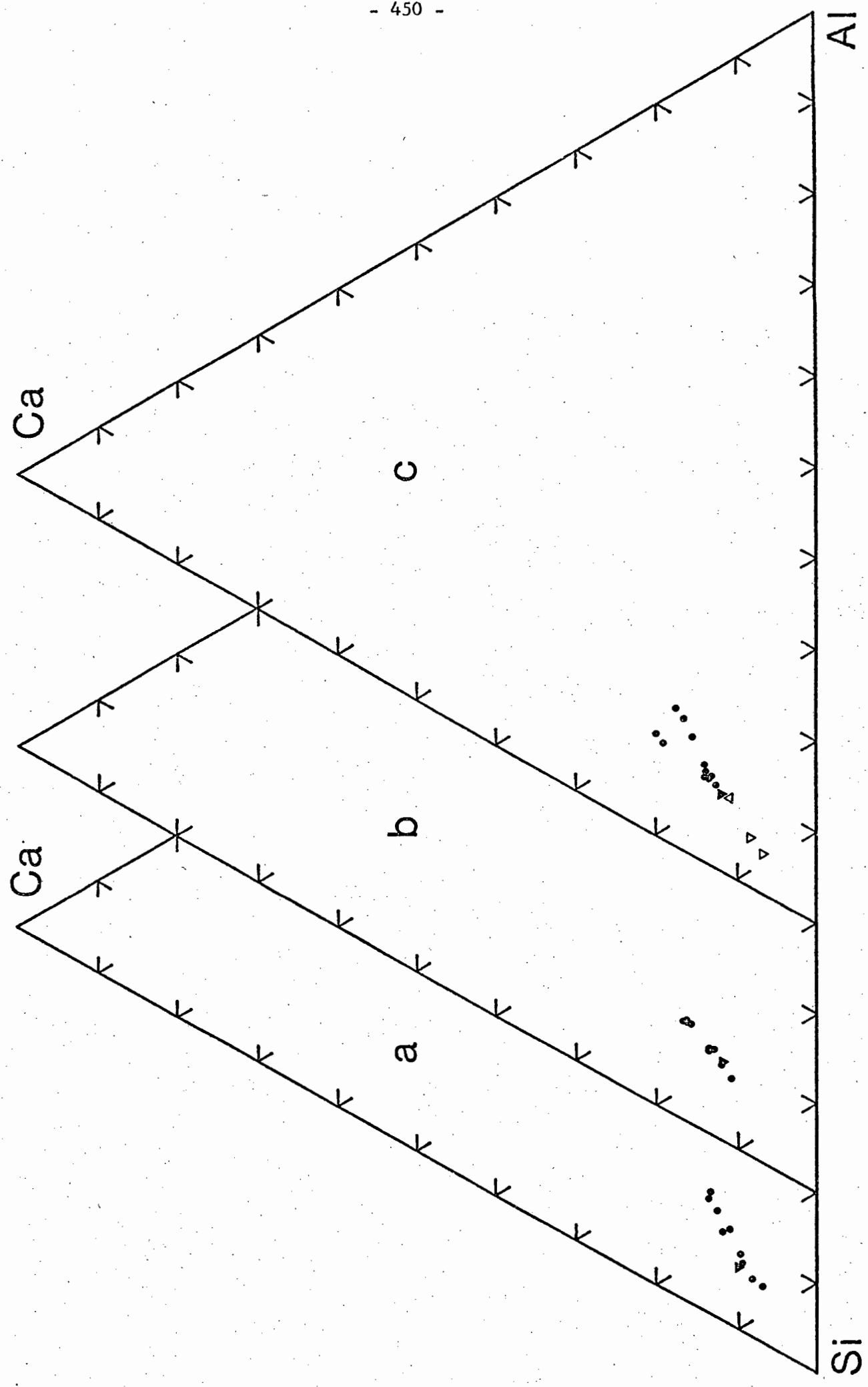
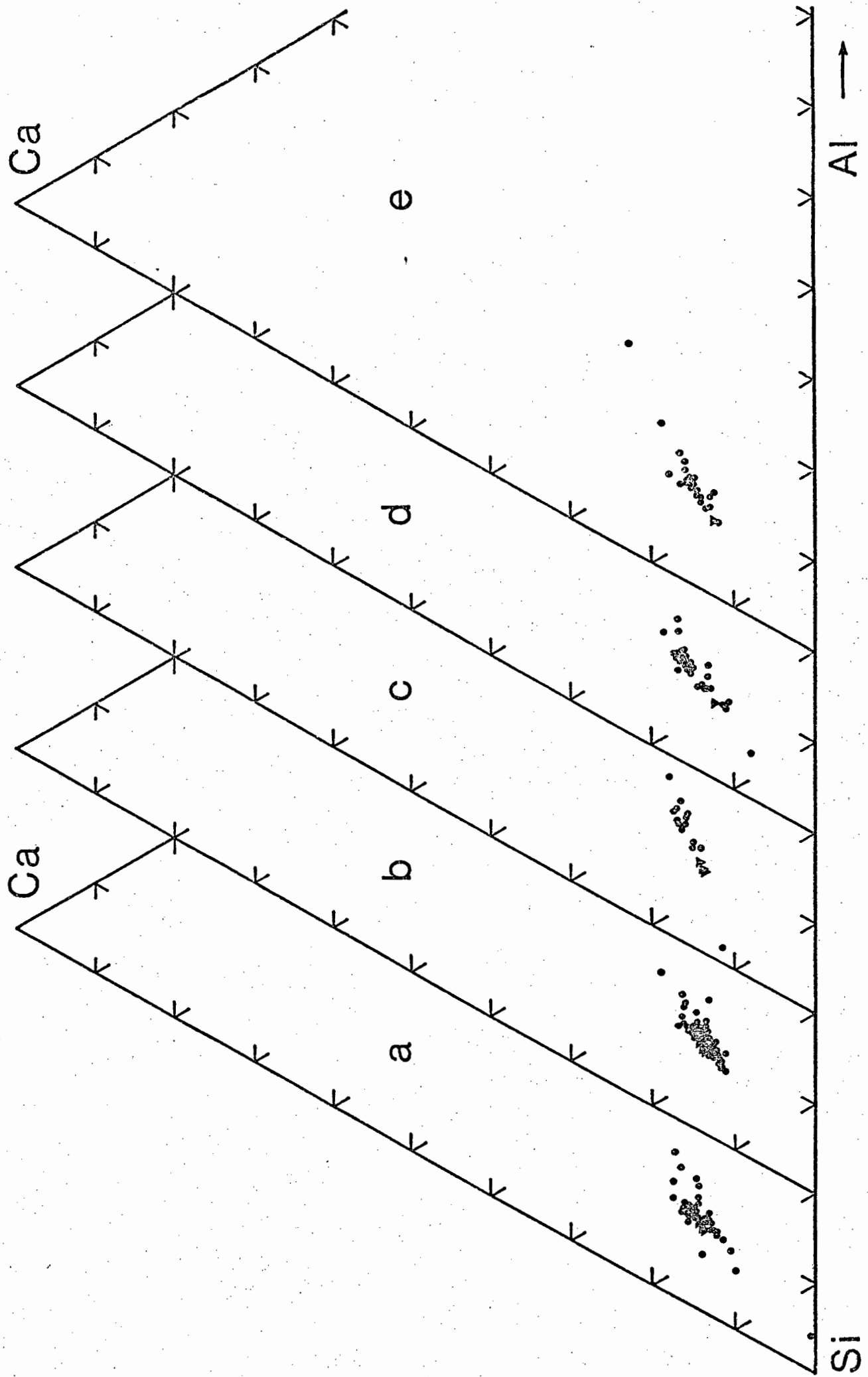


Fig. 7.34. The Ca-Si-Al relationship in glassy materials in Malvern and Molteno. 'True' glasses (a) and glassy microbreccias (b) in Malvern have similar compositional ranges and are concentrated around the four bulk analyses, whereas the devitrified glasses (c) are all richer in Ca and Al than the host meteorite. The glasses and glassy microbreccias of Molteno (d and e respectively) show variations similar to those of the equivalent phases in Malvern but do not cluster about the Molteno bulk composition.



the achondrite line (Fig. 7.34c). All of the devitrified varieties are enriched in Ca and Al relative to the howardite host.

Molteno

The glassy materials in Molteno plot in a compositional range on the achondrite trend similar to the ranges of the Malvern glasses and glassy microbreccias, but both varieties plotted extend a little beyond the eucrites of Fig. 5.29a. They differ from their counterparts in Malvern in not clustering around the bulk composition, but lie mainly on the Ca-Al side (Figs 7.34d and 7.34e).

7.4.6 The Si-Mg-Al relationship

Binda

The glassy microbreccias in Binda show a degree of variation in this relationship only a little less than the compositional range of the entire howardite series in Fig. 5.30a. The linear trend they form coincides with the achondrite trend only at the Mg-rich extremity; the divergence is towards the Al apex of the diagram (cf. Figs 7.29, 7.31a, and 7.33a). The trend does not include the bulk analyses, which plot on the achondrite line (Fig. 7.35a), and most of the glassy materials show greater richness in Al than these analyses.

Bununu

Bununu 'true' glasses show a limited range of variation coincident with part of the achondrite trend and are largely situated nearer the Si-Al side of the diagram than the composition of their host (Fig. 7.35b). The glassy microbreccias are all enriched in Si and Al relative to Bununu, and more than half plot in a dispersed extension of the howarditic part of the achondrite trend (Fig. 7.35c).

Frankfort

The glassy microbreccia in Frankfort shows enrichment in Si and Al relative to the bulk analyses, and plots on the achondrite trend (Fig. 7.35b).

Malvern

Fig. 7.36a shows that the glasses in Malvern form a slightly elongated cluster around the bulk analyses. The few points that do not lie in this cluster follow the general direction of the achondrite trend in Fig. 5.30a except for some that form a minor trend with approximately constant Si. The glassy microbreccias (Fig. 7.36b) cluster in a similar fashion, but some points plot on the eucrite sub-trend that is evident in Fig. 5.30a. The Malvern devitrified glasses do not coincide with the eucrites (Fig. 7.36c). They are richer in Al, and form a scattered extension to the achondrite trend.

Molteno

The glassy materials in Molteno are compositionally more variable than those in Malvern and, as observed in other plots, are displaced from the point that represents the host meteorite. As in Malvern, the more Si-rich glassy microbreccias plot on the eucrite sub-trend (Fig. 7.36e).

7.4.7 The Si-Mg-Ca relationship

Binda

Unlike the previous relationship, Fig. 7.37a reveals no significant divergence of the trend in the plotted glassy microbreccias in Binda from that of the achondrites and mesosiderites in Fig. 5.30b. The bulk analyses therefore plot on the trend defined by the microbreccias.

Bununu

Most of the Bununu glasses are enriched in Si and Ca relative to the bulk composition. Their limited trend is overlapped by some of the glassy microbreccias, but the remainder of these are irregularly distributed across the trend (Fig. 7.37b). This apparent trend may not be meaningful.

Fig. 7.35. The Si-Mg-Al relationship in glassy materials in Binda, Bununu, and Frankfort. Binda's glassy microbreccias (a) diverge significantly from the achondrite trend of Fig. 5.30a towards the Al vertex; the divergence increases with increasing Si and Al. The glasses in Bununu show a slight enrichment in Si and Al in comparison with the host composition (b). The glassy microbreccias (c) exhibit the same tendency, but in greater degree. The most Si- and Al-rich compositions form an irregular extension of the howarditic trend of Fig. 5.30a. The Frankfort compositions (open triangles in b) are related as in previous plots involving Si and Al.

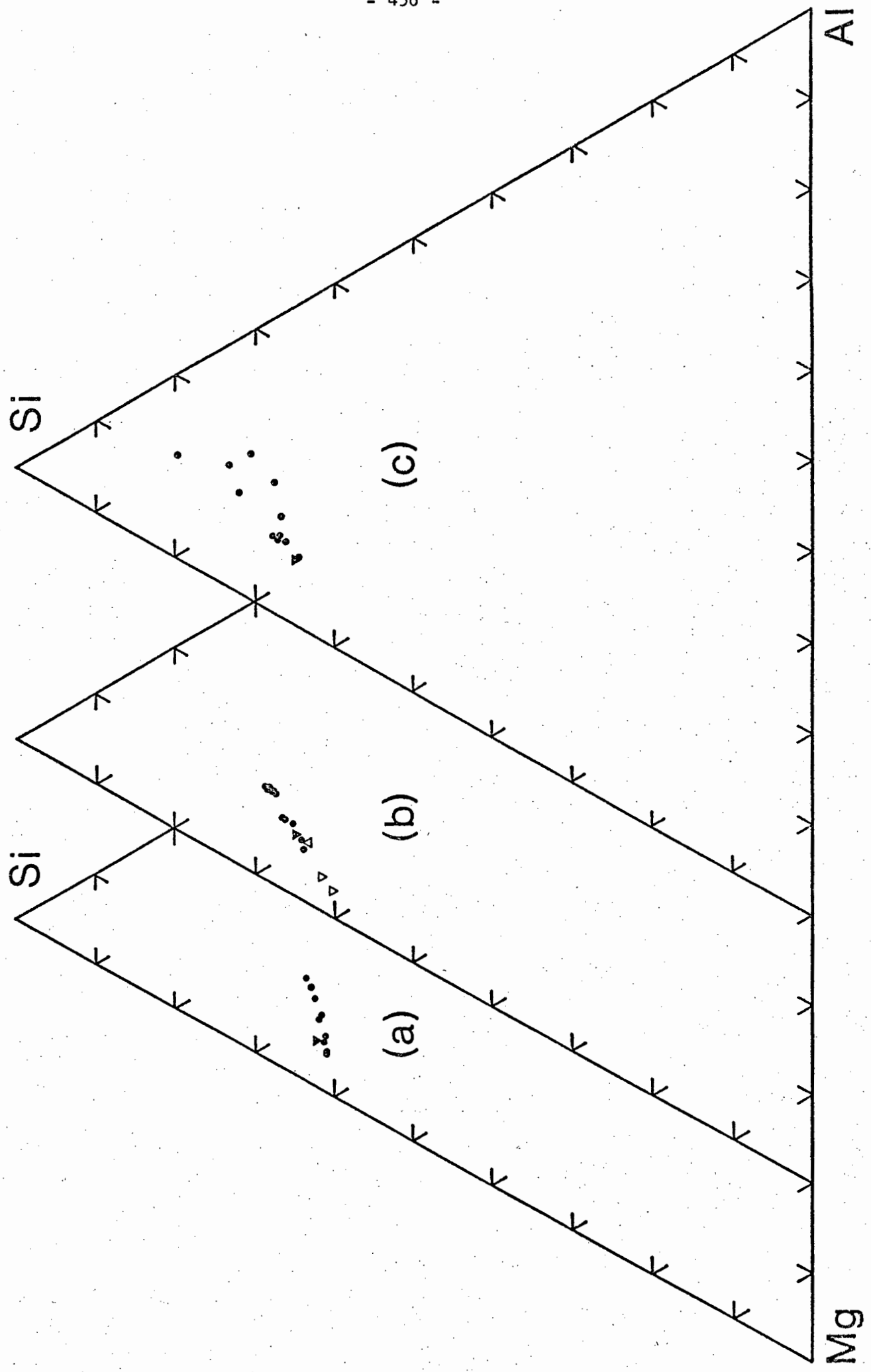
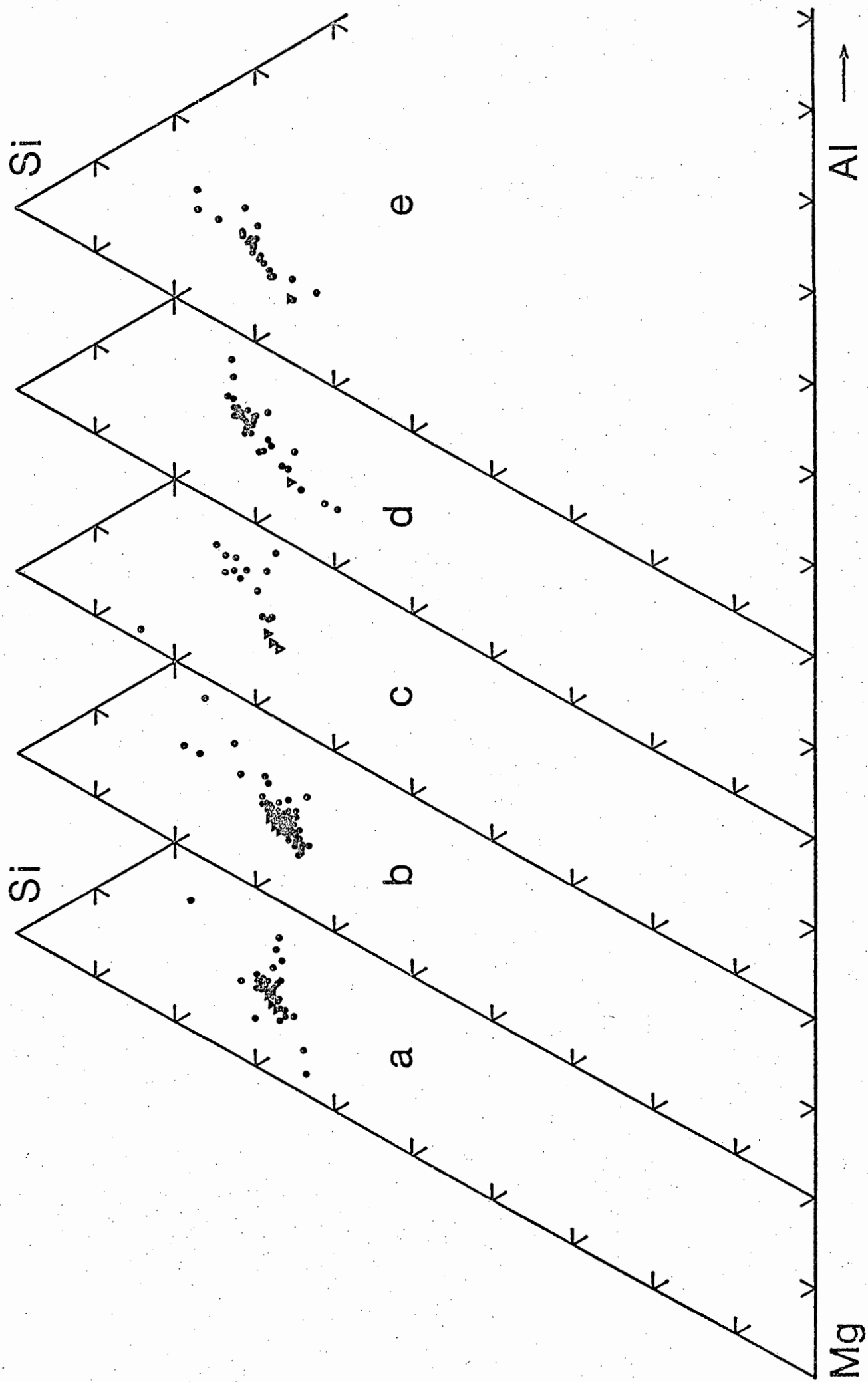


Fig. 7.36. The Si-Mg-Al relationship in glassy materials in Malvern and Molteno. In general, the Malvern glasses (a) and glassy microbreccias (b) are concentrated around the four bulk analyses, but the eucrite sub-trend of Fig. 5.30a is evident in the distribution of the microbreccias. Devitrified varieties all show enrichment in Si and Al relative to the host meteorite, and mainly plot rather irregularly on the extension of the howarditic part of the achondrite line (c). Relative enrichment in Si and Al is evident in the glasses (d) and glassy microbreccias (e) in Molteno, which generally plot on the achondrite trend.



Frankfort

As in previous plots, the sole glassy microbreccia in Frankfort lies on the achondrite trend and is richer in Si and Ca than both Frankfort (F) and Frankfort (T) (Fig. 7.37a).

Malvern

The Malvern 'true' glasses form a slightly elongated group that includes the bulk analyses but is slightly displaced towards Si; almost all the analyses fall within this grouping (Fig. 7.38a). The devitrified glasses (Fig. 7.38b) exhibit a fairly coherent distribution in the eucritic part of the achondrite trend, all being richer in Si and Ca than the bulk analyses. The distribution of the glassy microbreccias (Fig. 7.38c) combines characteristics of the plots of both types of glass; they cluster around the points representing the bulk composition in an elongated field, and extend into and beyond the eucrite field though in sparse concentration.

Molteno

Fig. 7.37c shows that the 'true' glasses in Molteno plot along almost the entire compositional range of the howardites and eucrites in Fig. 5.30b, and that all but three are richer in Si and Ca than the bulk analysis. Variation in the glassy microbreccias is less extensive than in the glasses, though their distributions are similar in other respects (Fig. 7.37d).

7.4.8 The Si-Mg-Fe relationship

Binda

The glassy microbreccias in Binda plot in a trend that traverses part of the mesosiderite field in Fig. 5.30c and cuts across the achondrite trend, on which the bulk composition falls (Fig. 7.39a). Fe is approximately constant in these microbreccias (cf. Fig. 7.27).

Fig. 7.37. The Si-Mg-Ca relationship in glassy materials in Binda, Bununu, Frankfort, and Molteno. In this plot, the glassy microbreccias in Binda (a) define a trend coincident with that of the achondrites in Fig. 5.30b. The Bununu glasses and glassy microbreccias (b) show only limited variation along the achondrite trend, with relative enrichment in Si and Ca in evidence. The cross-cutting trend in the microbreccias has no counterpart in Fig. 5.30b. The enrichment in Si and Ca in the Frankfort glassy microbreccia (upright open triangle in a) observed in preceding figures is confirmed in this plot. The glasses (c) and glassy microbreccias (d) in Molteno are distributed along the achondrite trend, almost without exception closer to the Si-Ca side of the plot than the host composition.

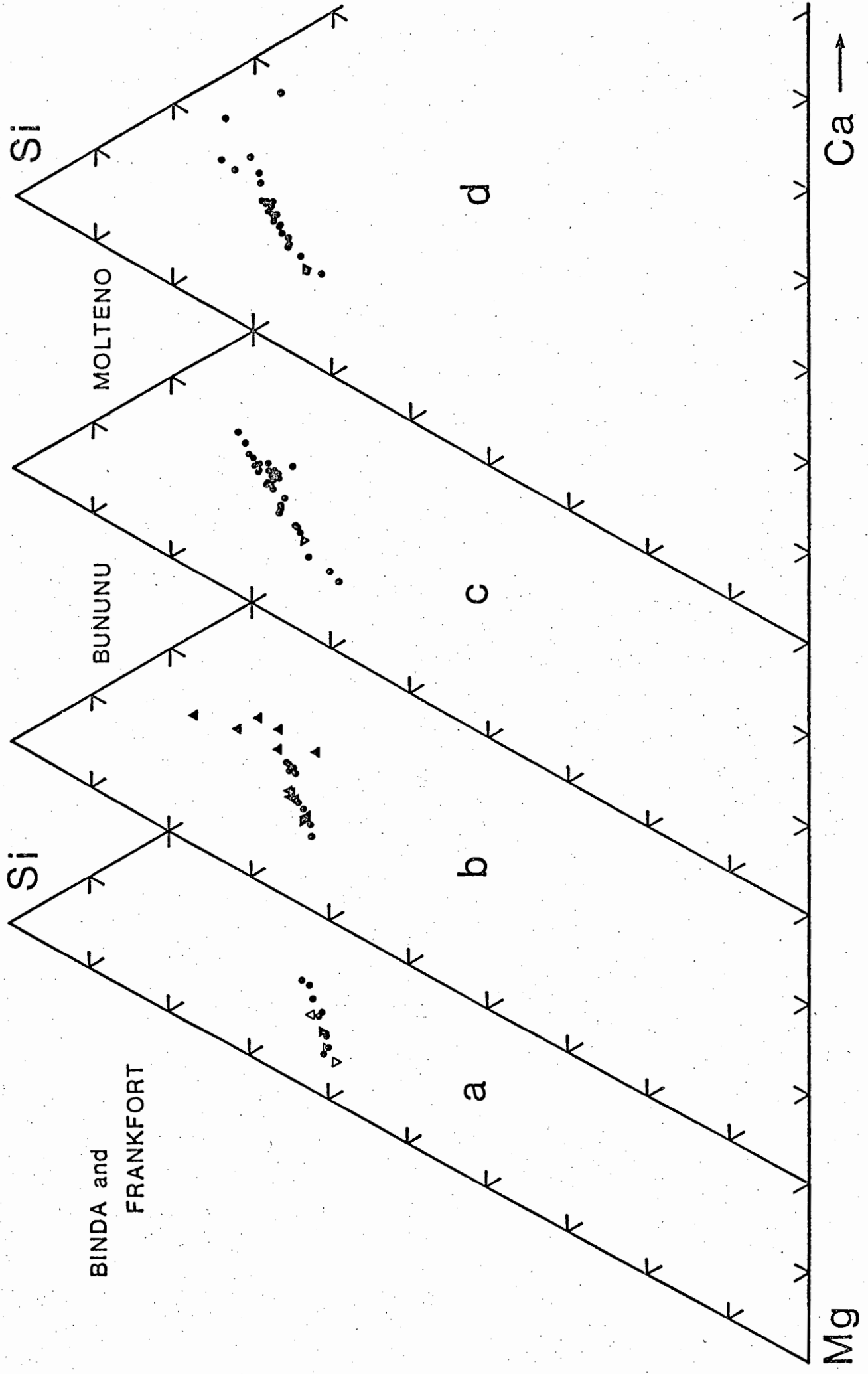
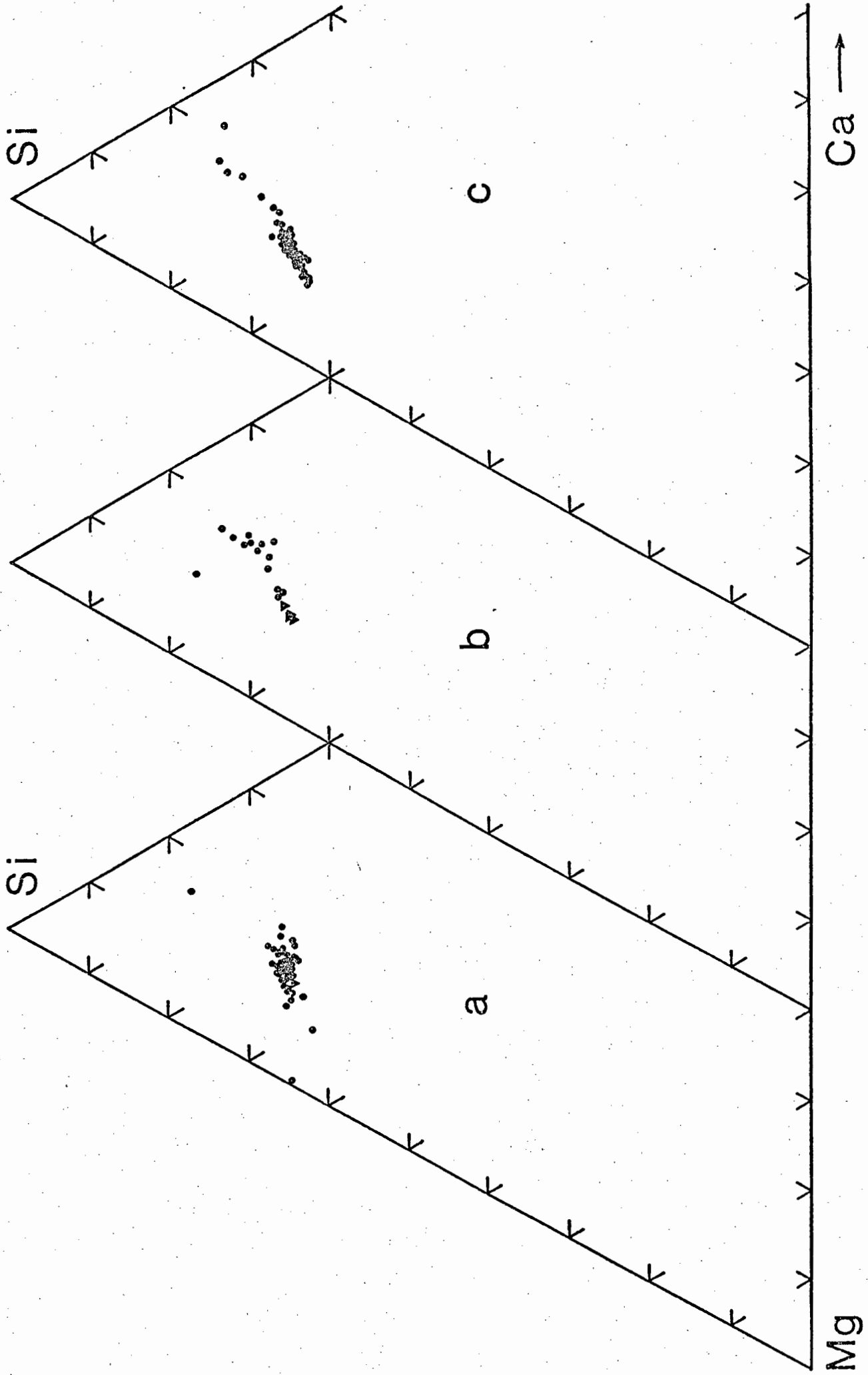


Fig. 7.38. The Si-Mg-Ca relationship in glassy materials in Malvern.

The 'true' glasses (a) show slight enrichment in Si, but can be considered to cluster round the bulk analyses in a field elongated in the achondrite trend. Enrichment in Si and Ca is evident in the devitrified glasses (b), which plot in the eucrite field. Most of the glassy microbreccias (c) are concentrated close to the host composition. A few, however, plot in the eucrite field.



Bununu

Bununu's glasses show limited variation in this plot (Fig. 7.39b). In general, they lie on the achondrite line and are enriched in Si and Fe relative to the host meteorite. This coherence is absent from the distribution of the glassy microbreccias, which occupy an irregular field stretching from the 'true' glasses towards the Si apex of the figure.

Frankfort

Frankfort's only glassy microbreccia plots on the achondrite trend and is richer in Si than either of the bulk analyses (Fig. 7.39a).

Malvern

The glasses in Malvern (Fig. 7.40a) and the glassy microbreccias (Fig. 7.40c) both concentrate close to the bulk analyses. The glasses show some enrichment in Fe in relation to these analyses. Such enrichment is not marked in the microbreccias. The slight elongation of the glassy microbreccia field, and the extension of that field to the Si-Fe side of the diagram, indicate that Fe remains constant while Si and Mg vary. The devitrified glasses in this howardite (Fig. 7.40b) plot in an irregular group richer in Si than the bulk analyses in this relationship.

Molteno

The majority of the glasses in Molteno fall rather irregularly on the achondrite trend of Fig. 5.30c. Most of the compositions are enriched in Si (some markedly so) and Fe relative to the host composition (Fig. 7.39c). The glassy microbreccias plot on the eucritic part of the achondrite trend, but show less variability than the glasses. Almost all display Si-enrichment over the bulk composition, with accompanying minor Fe-enrichment as in the glasses (Fig. 7.39d).

Fig. 7.39. The Si-Mg-Fe relationship in glassy materials in Binda, Bununu, Frankfort, and Molteno. The glassy microbreccias in Binda (a) define a trend of constant Fe in which most of the compositions are richer in Si than the bulk meteorite. This trend traverses both the mesosiderite field and the achondrite trend (Fig. 5.30c). The glasses in Bununu (circles in b) plot on the achondrite trend, as do some of the glassy microbreccias (triangles). The remainder show a high degree of enrichment in Si and plot in an irregular field. The Frankfort glassy microbreccia (open triangle in a) is similarly enriched relative to the meteorite's bulk composition. 'True' glasses in Molteno (c) plot irregularly on the achondrite trend; some are highly enriched in Si and form a distinct sub-trend that is present also in the distribution of the glassy microbreccias (d). Most of the microbreccias fall in the eucrite field, with slightly less variation than in the glasses.

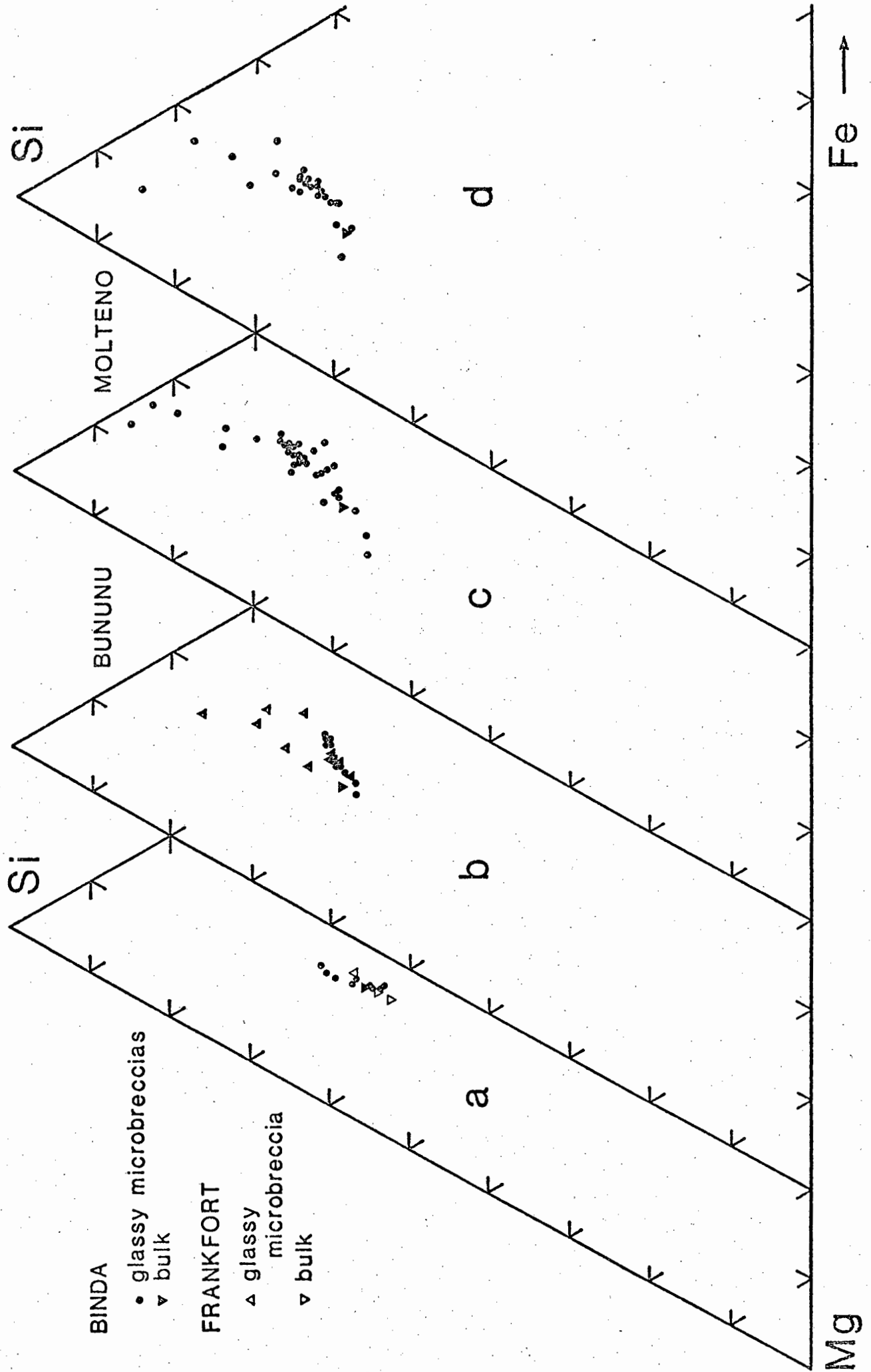
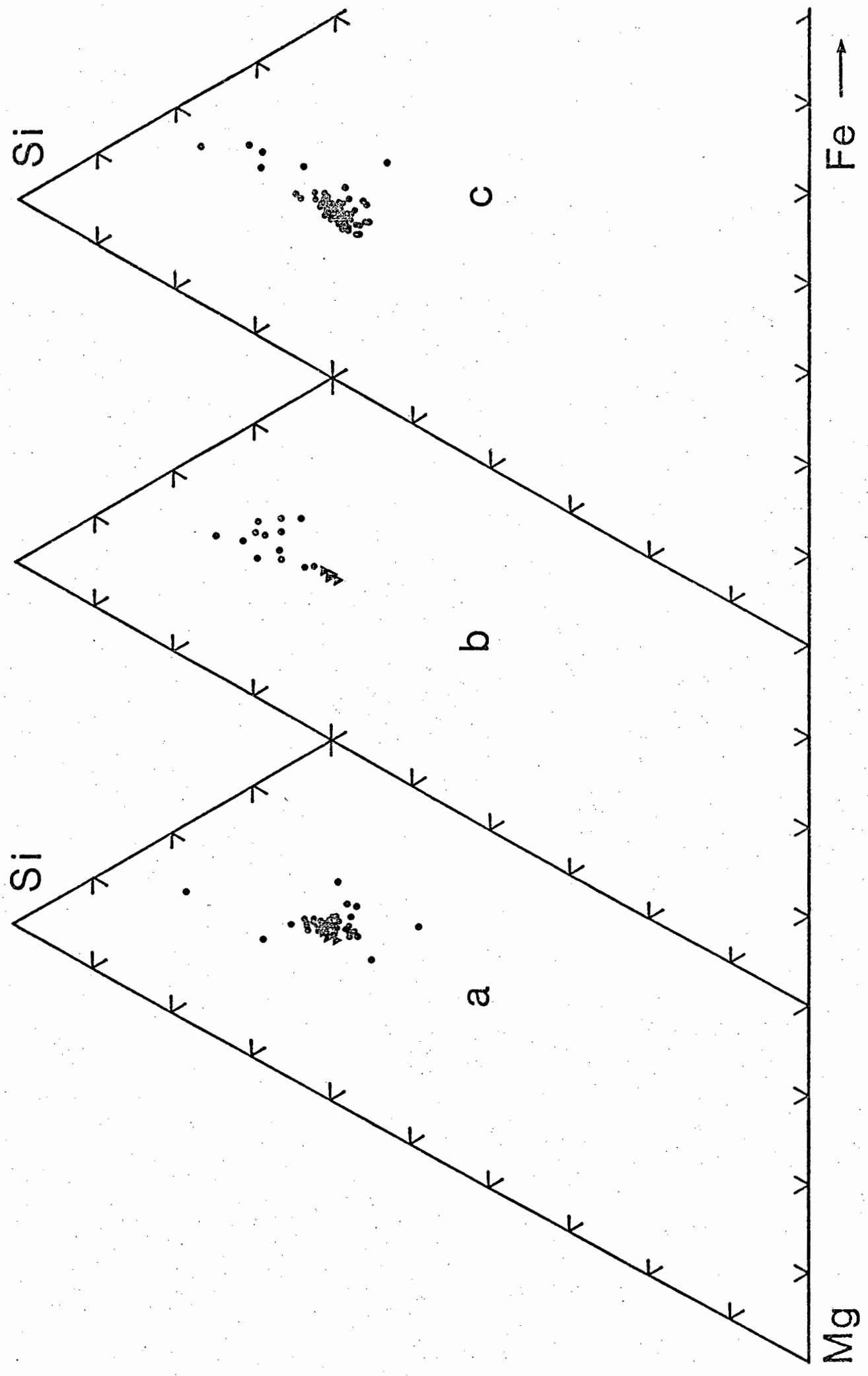


Fig. 7.40. The Si-Mg-Fe relationship in glassy materials in Malvern. Clustering around the bulk composition is evident both in the glasses (a) and in the glassy microbreccias (c). Those microbreccias that do not plot in the main concentration suggest the presence of a sub-trend of Si-enrichment (cf. Fig. 7.39, b, c, and d). The devitrified glasses (b) also are distributed in a way that indicates relative enrichment in Si while Fe remains approximately constant.



7.4.9 The Al-Mg-Fe relationship

Binda

Comparison of Figs 5.31a and 7.41a reveals that the glassy microbreccias in Binda bear little relation to the howardite trend or to the distribution of the eucrite series, which is quite distinct in this particular relationship. Variation in the microbreccias is limited to Al and Mg, as noted in other plots involving Fe. Most of the compositions are richer in Al than the bulk meteorite, which plots on the howardite trend. The microbreccia trend traverses the mesosiderite field defined in Fig. 5.31a.

Bununu

The Bununu glasses form a regular trend exactly coincident with part of the achondrite trend. All but one of the glasses is enriched in Al and Fe by comparison with the host composition (Fig. 7.41c). In the same figure, the glassy microbreccias lie in an irregular field partially superimposed on the glasses but, in general, including compositions enriched in Al relative both to the glasses and the bulk analysis.

Frankfort

The Frankfort glassy microbreccia lies on the howarditic section of the trend in Fig. 5.31a and is more Al-rich than the two bulk analyses plotted for comparison (Fig. 7.41a).

Malvern

The 'true' glasses in Malvern are rather scattered in this plot (Fig. 7.42a) but fall mainly in a grouping slightly displaced from the positions of the bulk analyses in the direction of the Al-Fe side. This concentration coincides with the most Fe-rich part of the howarditic trend. Devitrified varieties occupy an irregular field in the same figure. Almost all show a high degree of enrichment in Al in relation to the 'true' glasses. Malvern's glassy microbreccias (Fig. 7.42b) are loosely concentrated around

Fig. 7.41. The Al-Mg-Fe relationship in glassy materials in Binda, Bununu, Frankfort, and Molteno. The glassy microbreccias in Binda define a trend in which Fe remains fairly constant (a). This trend cuts across both the mesosiderite field and the achondrite line in Fig. 5.31a. The Bununu glasses (filled circles in c) plot on the achondrite trend and show enrichment in Al and Fe over the host composition. A few of the glassy microbreccias plot with the glasses but the remainder lie in an irregular field characterized by Al-enrichment. The glassy microbreccia in Frankfort also is richer in Al than the bulk analyses of the meteorite (open triangles in a). Molteno glasses (filled circles in b) are distributed irregularly along the achondrite trend, and most of the glassy microbreccias plot similarly. There is considerable scatter in both distributions, but most of these glassy phases are markedly richer in Al than the bulk analysis.

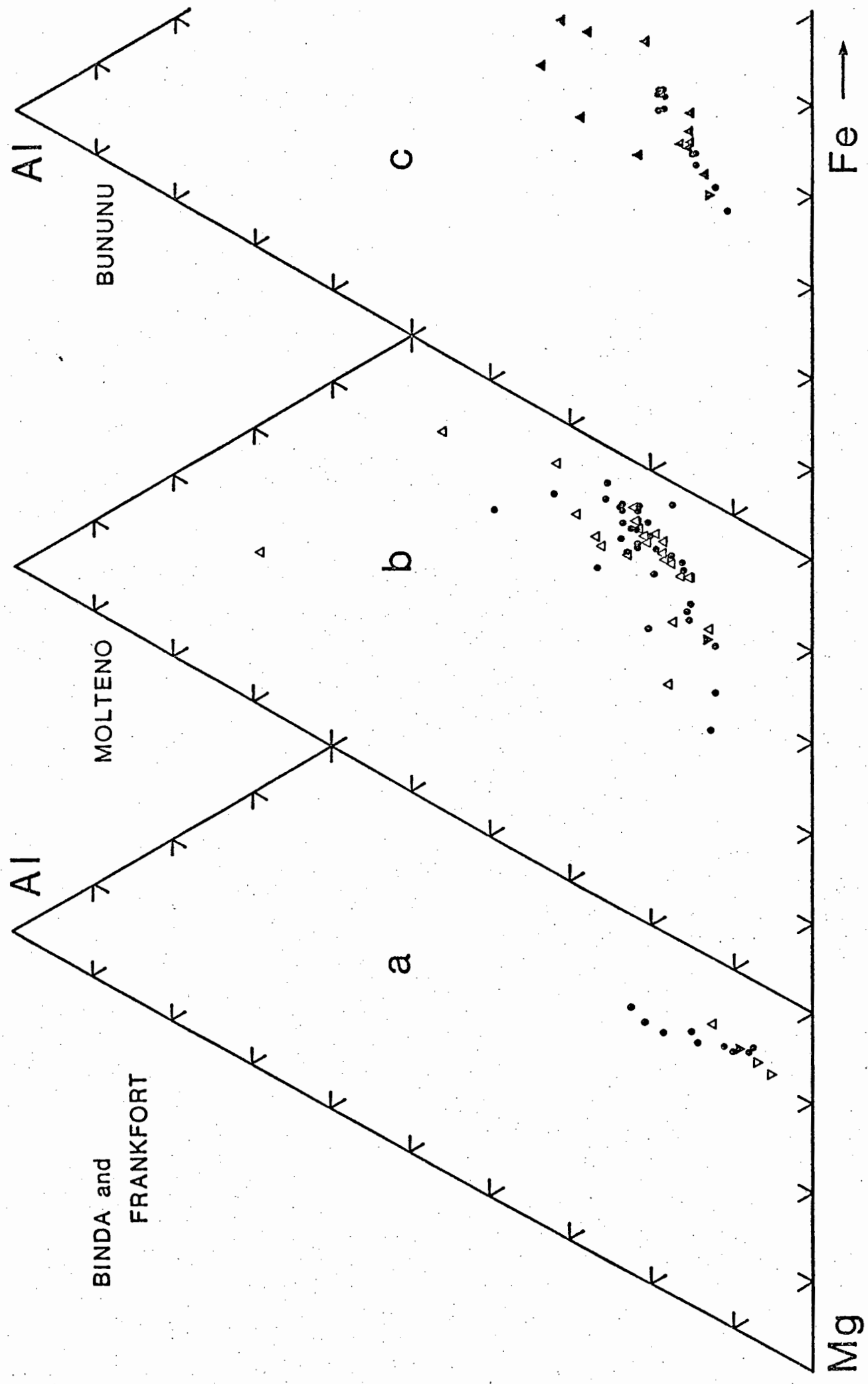
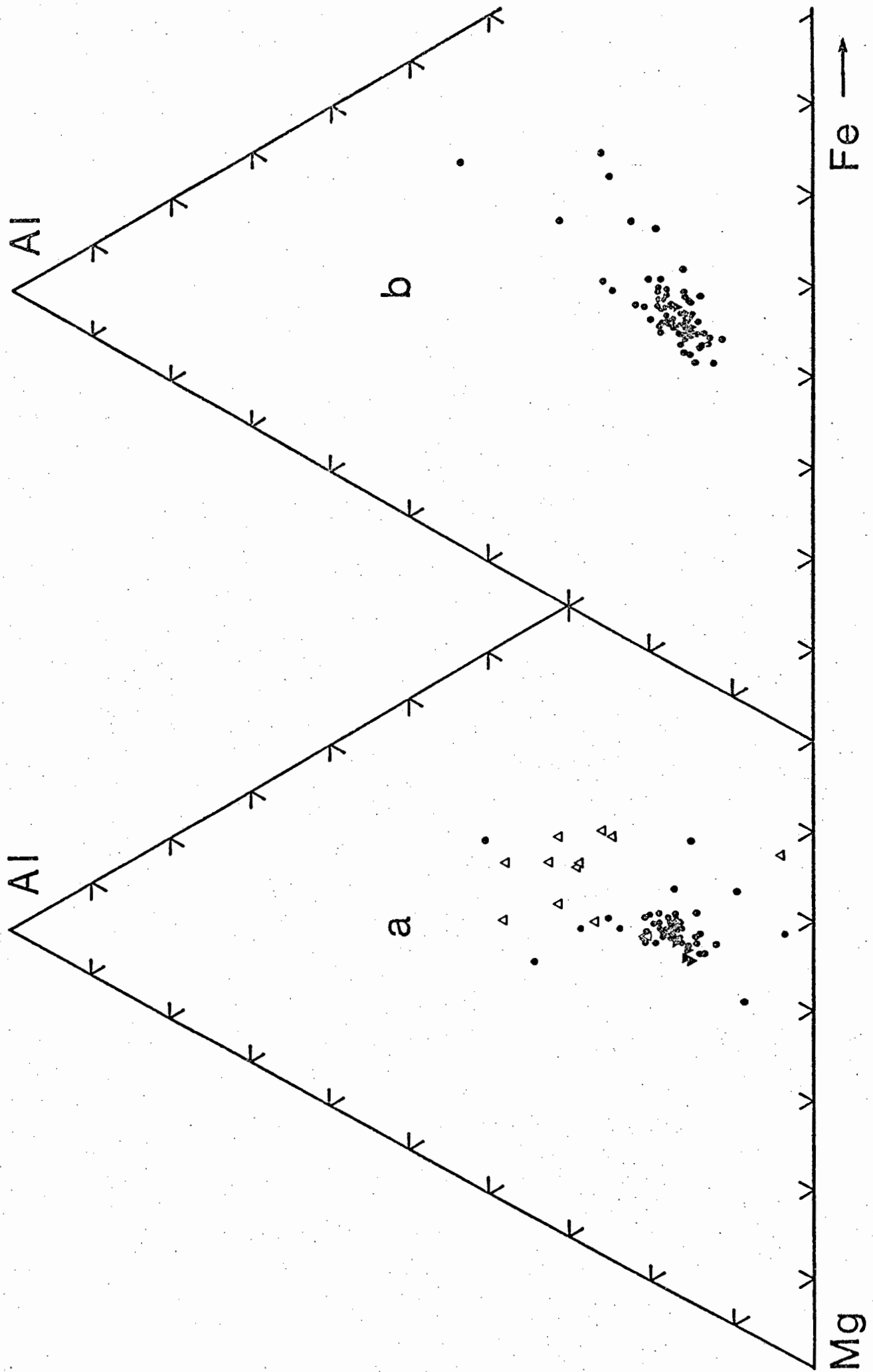


Fig. 7.42. The Al-Mg-Fe relationship in glassy materials in Malvern.

Both 'true' glasses (solid circles in a) and glassy microbreccias (b) show clustering in the vicinity of the bulk analyses, but the former are slightly enriched in Fe. Some of the glassy microbreccias form a scattered extension to the howarditic trend of Fig. 5.31a. Devitrified glasses (open triangles in a) occupy an irregular field similar to that of the Al-rich glassy microbreccias in Bununu (Fig. 7.41c).



the four bulk analyses. The cluster shows some alignment with the achondrite trend, but marked enrichment in Al and Fe is absent except in a small number of analyses that plot on an extension of the trend.

Molteno

Considerable scatter is present in the distribution of Molteno's 'true' glasses (Fig. 7.41b), almost all of which are considerably richer in Al and Fe than the host composition. The points representing these glasses are, however, irregularly distributed along the achondrite trend up to, and beyond, the junction of the howardites with the eucrite sub-trend (see Fig. 5.31a). The glassy microbreccias in the meteorite have a distribution similar to that of the glasses, but with slightly less compositional variation along the achondrite trend (Fig. 7.41b).

7.4.10 The Si-Al-Fe relationship

Binda

Distributions in this relationship are condensed (see Fig. 5.31b), but Fig. 7.43a shows that the glassy materials in Binda do not conform to any of the trends established for the bulk achondrites and the silicates of the mesosiderites. Nor does their distribution show constancy of the Fe component, as in some preceding plots, but enrichment in Al relative to the Binda bulk composition is indicated.

Bununu

Bununu's 'true' glasses (Fig. 7.43b) plot partly on the howarditic trend that links the diogenitic and eucritic trends (Fig. 5.31b), and partly on the eucritic trend. The tendency for these glasses to fall into two sub-groups may be seen in almost all the other relationships studied in this section, but the difference in the affinities of these sub-groups is most clearly demonstrated in this plot as a result of the wide angular divergence

of howarditic and eucritic trends. The glassy microbreccias in the meteorite (Fig. 7.43b) do not exhibit this tendency; they occupy an irregular field that denotes their higher contents of Si and Al in relation to the glasses and, in general, to the host composition.

Frankfort

The glassy microbreccia in this howardite plots on the howardite line and is enriched in Al relative to the analyses of Frankfort (F) and Frankfort (T).

Malvern

Malvern's 'true' glasses present a somewhat scattered distribution in Fig. 7.44a, but essentially cluster close to the bulk analyses; there is a slight displacement indicative of enrichment in Al and Fe. Outlying points in the distribution are not aligned with any of the trends in Fig. 5.31b. Devitrified glasses are totally displaced from the positions of the bulk compositions in the direction of the Al apex of the figure (Fig. 7.44b). A similar, but lesser, displacement is evident in the glassy microbreccias, which plot in a very compact cluster that is not, however, exactly centred on the Malvern bulk composition (Fig. 7.44c).

Molteno

Clustering of the points representing the glasses in Molteno is evident in Fig. 7.43c, with the maximum density of points falling on the eucrite sub-trend, i.e. nearer to the Al apex of the plot than the host composition. The glassy microbreccias in the meteorite are distributed in a very similar fashion (Fig. 7.43d), but with slightly less relative enrichment in Al than shown by the 'true' glasses.

Fig. 7.43. The Si-Al-Fe relationship in glassy materials in Binda, Bununu, Frankfort, and Molteno. The trend defined by Binda's glassy microbreccias cuts across the distributions of the achondrites and mesosiderites established in Fig. 5.31b. Most of the microbreccias (a) are enriched in Al relative to the bulk meteorite. The glasses in Bununu (circles in b) lie partly on the howardite trend and partly in a group aligned with the eucrite trend. These, and the irregularly distributed glassy microbreccias plotted with them, show some enrichment in Al. Frankfort's only glassy microbreccia (a) is similarly enriched and plots in the position of the achondrite line. Molteno's glasses (c) and glassy microbreccias (d) are concentrated on the eucrite trend. Both materials are richer in Al in this plot than the host meteorite.

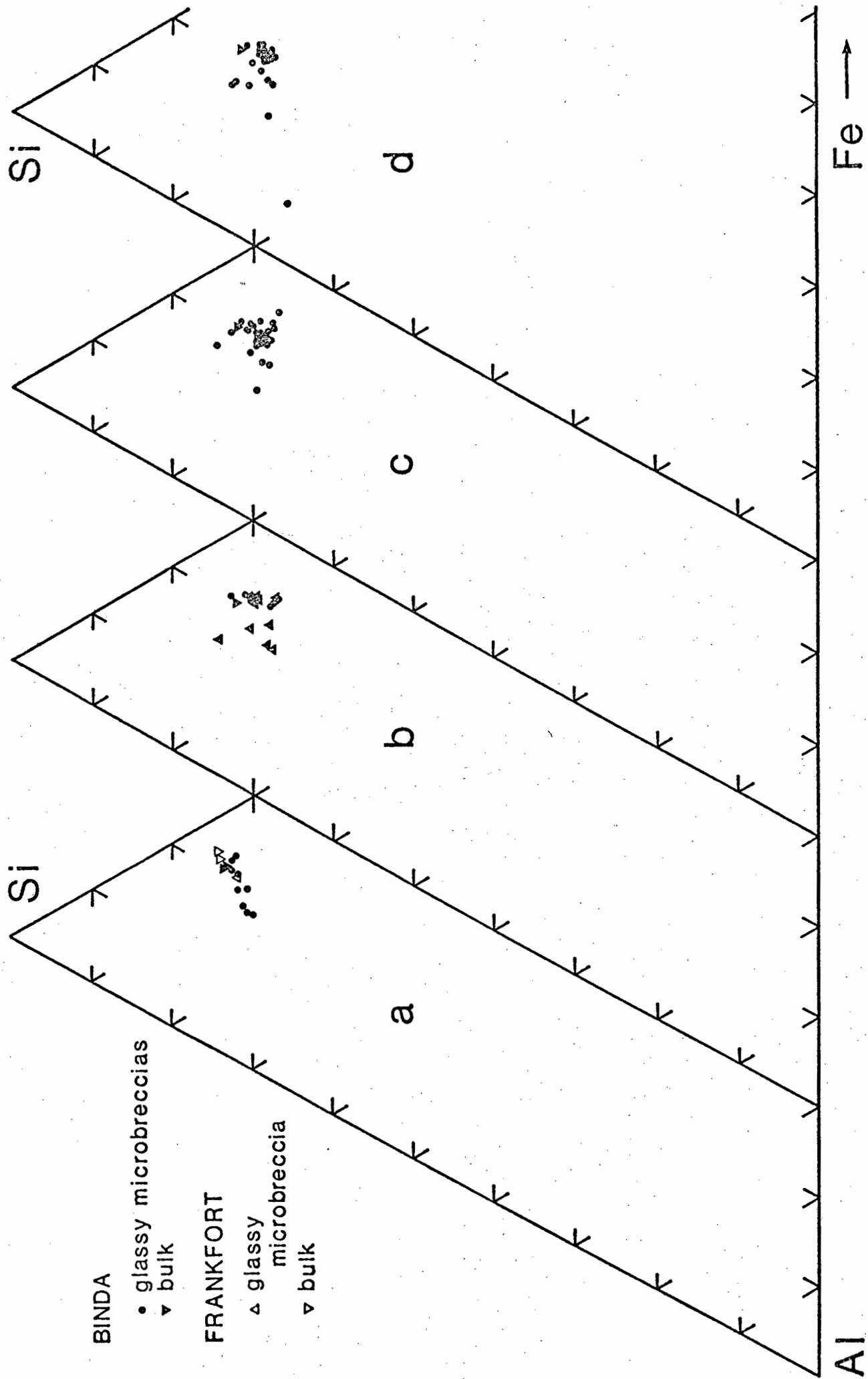
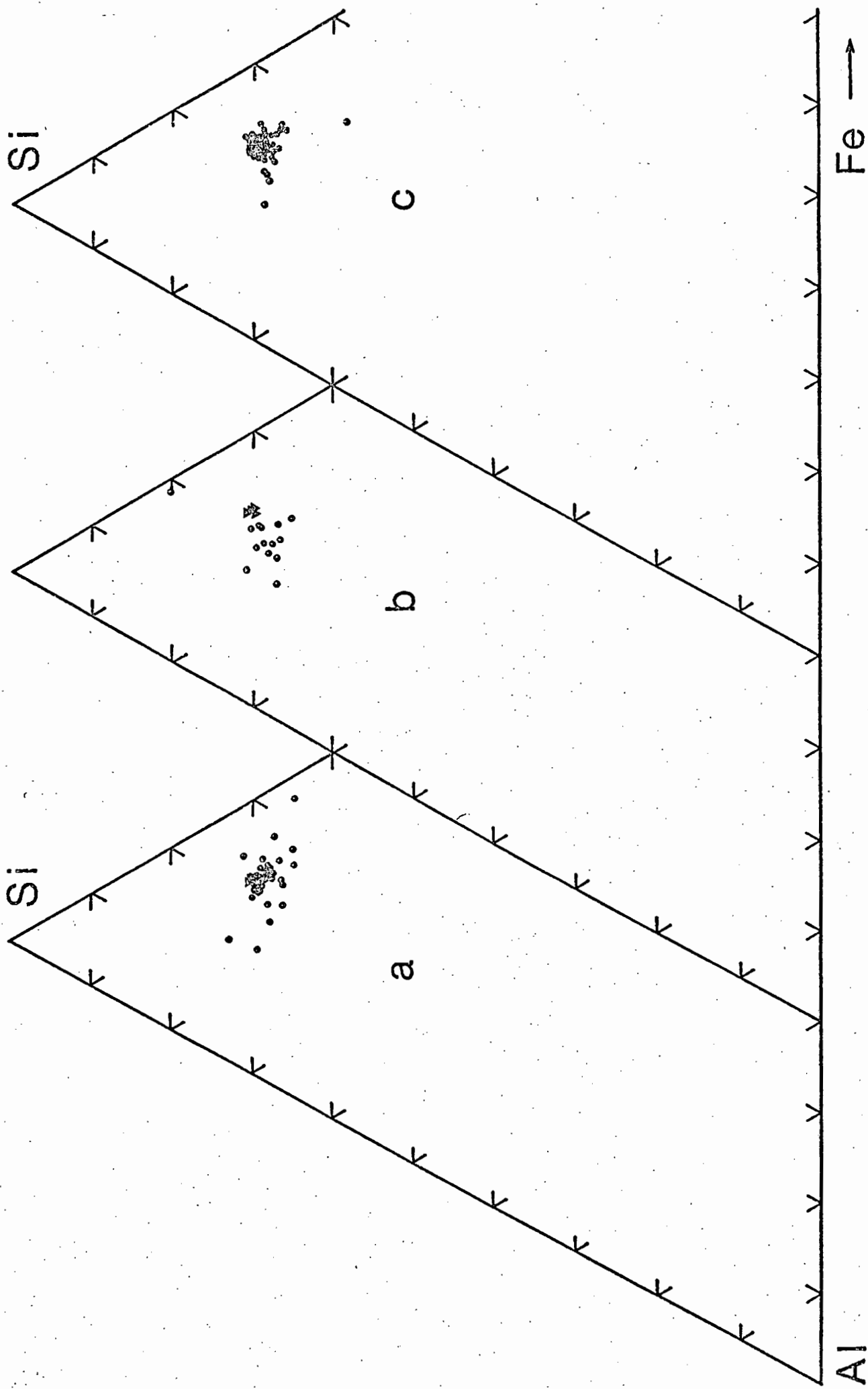


Fig. 7.44. The Si-Al-Fe relationship in glassy materials in Malvern. 'True' glasses (a) and glassy microbreccias (c) are concentrated close to the four bulk analyses; the displacement is slight, especially for the microbreccias, and is in the direction of the Al-Fe side of the diagram. The devitrified glasses occupy an irregular field that indicates enrichment in Al, but not in Fe, relative to the bulk composition (b).



7.4.11 The Si-Ca-Fe relationship

Binda

The similarity between this relationship and the previous one is clear in the distribution of Binda's glassy microbreccias in Fig. 7.45a; their trend has the cross-cutting relationship to achondrites and mesosiderites noted in Fig. 7.43a. In this instance, however, no marked relative enrichments are present, and the host composition plots in the middle of the trend.

Bununu

In Fig. 7.45b, the 'true' glasses in Bununu plot in two distinct groups, one on the howardite trend, the other on the eucrite trend, of Fig. 5.31c. All show enrichment in Ca relative to the bulk analysis. This enrichment is present also in the glassy microbreccias, which plot in an irregular group that extends beyond the eucrites in the same figure.

Frankfort

The Frankfort glassy microbreccia plots on the achondrite trend and is richer in Ca than the corresponding bulk analyses (Fig. 7.45a).

Malvern

As in the Si-Al-Fe relationship, the glasses and glassy microbreccias in Malvern cluster round the bulk compositions (Figs 7.46a and 7.46c respectively). The microbreccias show less scatter than the glasses, and lack their slight enrichment in Ca and Fe in relation to the bulk analyses. The devitrified glasses coincide approximately with the eucrite trend of Fig. 5.31c, and are almost all richer in Ca than the host meteorite (Fig. 7.46b).

Molteno

The distributions of glasses and glassy microbreccias in Molteno are very similar to one another (Figs 7.45c and 7.45d respectively). Both show a fair degree of concentration at the junction of the howardite and

Fig. 7.45. The Si-Ca-Fe relationship in glassy materials in Binda, Bununu, Frankfort, and Molteno. The microbreccias in Binda (filled circles in a) plot transversely to the trends of the achondrites and mesosiderite silicates observed in Fig. 5.31c and, as a group, are not enriched in Ca relative to the host composition. The disposition of glasses (filled circles) and glassy microbreccias (open triangles) in Bununu (b) is similar to that of Fig. 7.43, with enrichment in Ca instead of Al; this observation is true also of the glassy clast in Frankfort (open triangle in a), and of the distributions of 'true' glasses and glassy microbreccias in Molteno (c and d respectively).

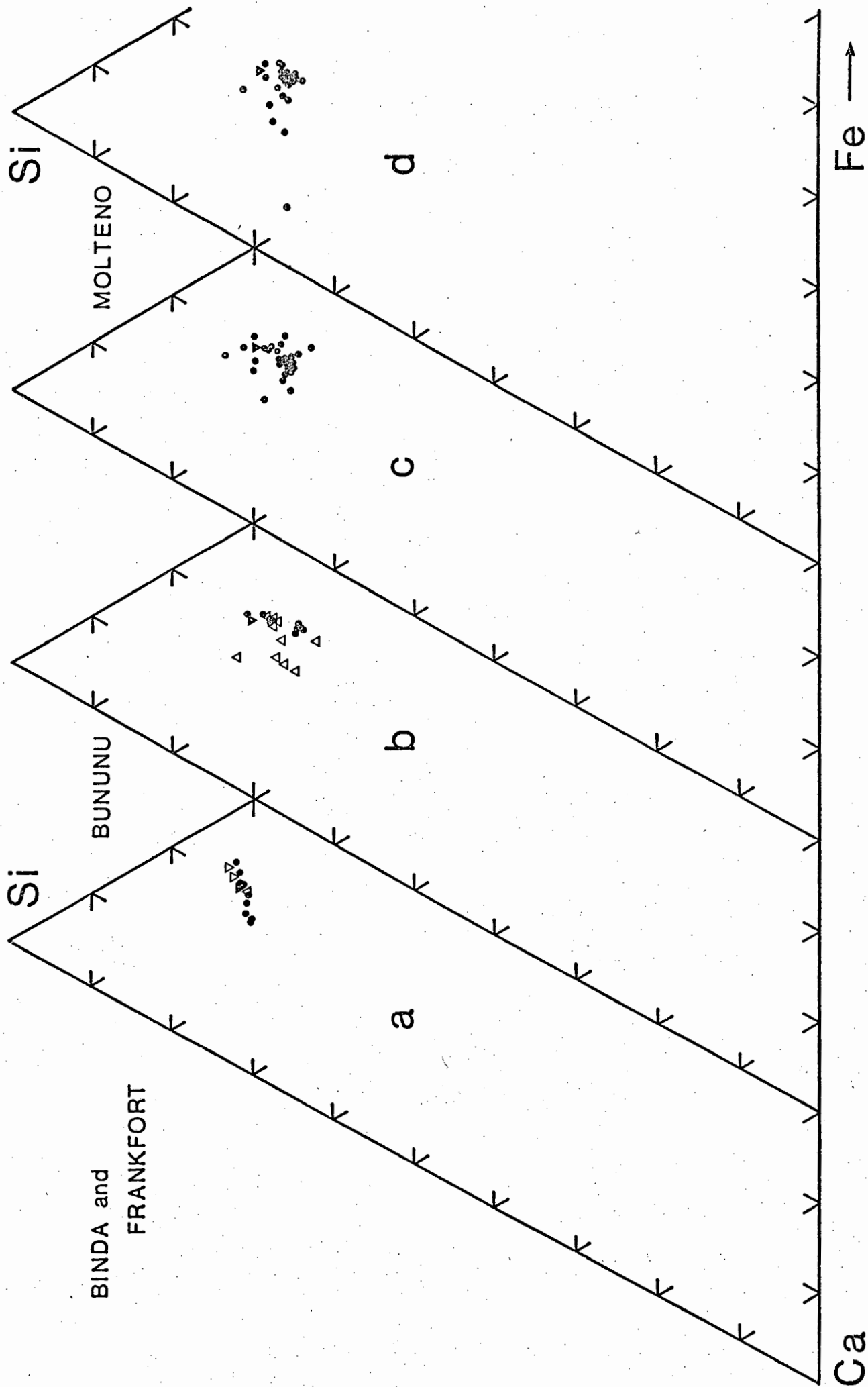
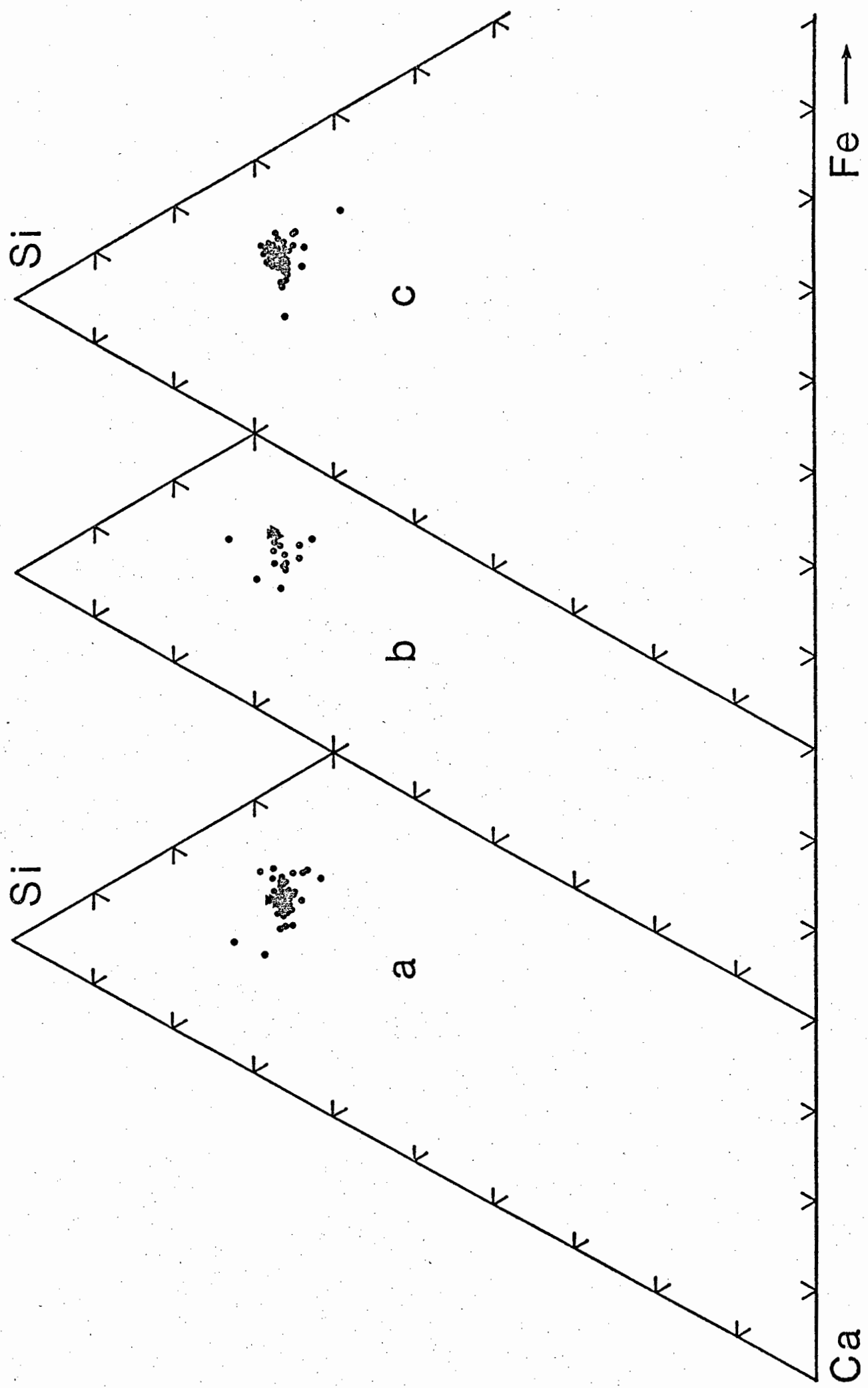


Fig. 7.46. The Si-Ca-Fe relationship in glassy materials in Malvern. The distributions of these phases - glasses (a), devitrified glasses (b), and glassy microbreccias (c) - are similar to those of Fig. 7.44, with enrichment in Ca instead of in Al. As in Fig. 7.44, the glassy microbreccias display the closest approximation to the bulk composition of the host meteorite.



eucrite trends established in Fig. 5.31c, and are therefore enriched in Ca and, to a lesser extent, Fe relative to the host composition.

7.4.12 Generalized observations on major element distributions in the glassy materials

In the inter-element relations considered above, certain general characteristics can be discerned in addition to features that apply only to particular meteorites. A summary of these characteristics follows:

Binda

Binda does not, in general, follow patterns established in the other four meteorites. Its glassy microbreccias plot in linear trends, with no tendency to concentrate in the vicinity of the bulk composition. These trends do not coincide with those established for bulk analyses of basaltic achondrites or the silicate fractions of mesosiderites. The glassy microbreccias do, however, show the enrichment in Ca and Al relative to the bulk composition that is prevalent in the four howardites.

Bununu

The glassy materials in Bununu invariably plot on the trend defined by the bulk achondrites or, generally irregularly, on an extension of that trend. The enrichment in Ca and Al, though present in both glasses and glassy microbreccias, is more marked in the latter, which plot beyond the eucrite field in relationships involving these two elements. The 'true' glasses tend to plot in two discrete groups, one in the howarditic part of the achondrite trend, the other in the eucritic section.

Frankfort

The only glassy phase in Frankfort consistently shows enrichment in Ca and Al relative to the two bulk analyses, and plots with them on the achondrite trend in all the relationships considered.

Malvern

Although the glassy materials in Malvern are compositionally variable, as in the other four meteorites, they alone display a tendency towards concentration around the plotted position of the bulk meteorite. Points that do not lie in the main concentrations are not randomly distributed, but plot on the achondrite trend. Clustering of the analyses is not restricted to any particular combination of major elements. The devitrified glasses do not conform to these generalizations. They are markedly enriched in Ca and Al, and plot irregularly in and beyond the eucrite field. Only slight enrichments in these elements are evident in the glasses and glassy microbreccias of Malvern.

Molteno

In general, the glassy materials in this howardite display a high degree of compositional variability, but plot regularly on the trend defined by the bulk analyses of the basaltic achondrites. They are generally substantially enriched in Ca and Al in relation to the composition of the host meteorite.

7.4.13 Implications of the major element distributions for the formation of the glassy materials

Certain conclusions emerge from the observations summarized above that have a bearing on the processes of formation of glassy phases in the five meteorites studied and that supply information on the materials from which the glasses were derived. These are:

(1) The points representing analyses of glassy materials in the various meteorites are generally distributed along the trend of the basaltic achondrites, or part of that trend. Binda is an exception and is discussed below. This variability of compositions is present to a limited degree even in most

of the inter-element relationships in Malvern, whose glassy materials show the closest approximation to the bulk composition of the host meteorite, i.e. the nearest approach to complete fusion of the regolithic debris from which the howardite was formed. The coincidence of the compositional variations with the basaltic achondrite trend indicates the operation of controls on these variations; they are not random, and are invariably far greater than analytical uncertainties.

(2) The compositional variations could have been produced in two ways that can be reconciled with the observational data. Firstly, a range of materials representing the compositions that make up the greater part, i.e. all but the most magnesian extremity, of the basaltic achondrite trend could individually have undergone complete fusion. The resulting glasses were then distributed throughout the planetary regolith to produce the observed lack of inter-clast uniformity. However, this does not conform completely with the petrographic data in Chap. 3, which indicates that although some of the glassy bodies were contributed to a particular part of the regolith in either a solidified or plastic form, others were formed in situ by impact. An alternative process by which a range of compositions could have been produced involves varying degrees of fusion of material incorporated during the formation of impact-generated glasses. If the fused material were itself related to the achondrite trend, the resultant effect would 'mimic' differentiation processes and the range of modified compositions would coincide with the trend, but would be displaced from the position of the bulk analysis, which represents a rough average of the regolithic material in the immediate vicinity of the point of origin of the meteorite. This is in fact observed in almost all the relationships studied; the compositions of the glassy phases are displaced along the trend, away from the position of the host composition towards higher relative values of Ca and Al.

(3) It is significant that the enrichment is invariably in these two elements. In ternary relationships not involving Ca and Al, minor enrichments in Si and Fe were noted, but there is never a trend of enrichment in Mg, the other major element included in the study. Enrichment in Ca and Al can be explained in two ways - fusion, or partial fusion, of included plagioclases, and partial devitrification through quench crystallization of orthopyroxene microlites such as reported by HEWINS and KLEIN (1978) (see section 3.5.2). It is probable that both processes operated, though perhaps not in the same glassy body. The petrographic investigation produced positive evidence of partial fusion of plagioclase clasts included in glassy materials, e.g. in glasses in Bununu (section 3.3.2), in which plagioclase inclusions display marked rounding and resorption whereas included pyroxene clasts are unaffected. Such observational evidence is supported by studies of naturally- and experimentally-shocked basalts from the Lonar Impact Crater, India (KIEFFER et al., 1976) and of glass-lined lunar microcraters (SCHAAL et al., 1976) that demonstrated that labradorite is fused to glass at shock intensities capable only of granulating augite and pigeonite crystals.

(4) The position of the bulk analysis of the howardite in relation to those of its glassy constituents in the inter-element relationships plotted is critical to an understanding of the source materials from which the glasses were formed. In Bununu, Frankfort, and Molteno the bulk composition plots at, or near, the end of the trends defined by the glassy components. Very few compositions of the glassy materials in these howardites therefore remain unexplained by a two-stage formation involving fusion of fragmental debris with an aggregate composition similar to that of the host meteorite, and modification of the melt by the processes of selective fusion of plagioclase and quench crystallization detailed in (3). It may be deduced, therefore, that the contribution made to these three howardites by exotic glasses with

compositions similar to more magnesian members of the bulk achondrite trend was minor; the petrographic data are in accordance with this deduction.

(5) In this respect, Malvern is different from the other three howardites.

A substantial proportion of the plotted glassy phases lies on the Ca-, Al-poor side of the host composition. This implies the addition of exotic glasses formed from materials more magnesian than Malvern. Glasses richer in Ca and Al may also have been contributed to the breccia, but their presence is less easy to detect. The petrographic examination of Malvern, in revealing the existence of glassy bodies (or fractured parts of such bodies) that have sharp, clearly defined boundaries and that do not intrude the surrounding 'matrix', more clearly supports a contribution of exotic glass to this meteorite than to the others.

(6) Exotic glassy materials may themselves have been modified at their place of formation by selective fusion of plagioclase and quench crystallization of orthopyroxene microlites. If so, this - together with the higher melting points of Mg-rich materials - may explain the absence of compositions at the magnesian extremity of the basaltic achondrite trend observed throughout the plotted inter-element relationships, and the tendency for the glassy phases to extend this trend to compositions richer in Ca and Al than the bulk eucrites plotted in the corresponding control diagrams presented in Chap. 5.

(7) The role played by extensive devitrification is clearly demonstrated by the devitrified glasses in Malvern. These phases invariably show considerable enrichment in Ca and Al relative to the host composition, and this is presumably attributable to processes already discussed. However, they show a tendency to be irregularly distributed in inter-element plots by comparison with glasses in which devitrification is less pronounced. It is suggested that this irregularity results from the crystallization of phases other than orthopyroxene, e.g. plagioclase, in the more advanced stages of devitrification exhibited by these Malvern glasses.

(8) Confirmation of the style of enrichment of the glassy materials in all five meteorites comes from the normative data plotted in Figs 6.1 - 6.6.

These plots show that the glassy materials are all displaced from the plotted positions of their corresponding bulk norms towards the feldspar apex of the appropriate diagram. Furthermore, the minor tendency noted in the Malvern glasses (Fig. 6.2) and glassy microbreccias (Fig. 6.4) towards enrichment in normative olivine may be an expression of the presence of exotic materials from more Mg-rich sources, as discussed in (5). Significantly, this minor trend is absent from the normative plots of glassy phases from the other meteorites and from that of the Malvern devitrified glasses.

(9) The summary of the general characteristics of the glassy microbreccias in Binda (section 7.4.12) indicates that their source materials had compositions slightly, but significantly, different from those from which the glassy phases in howardites were derived. This is most clearly apparent in ternary relationships involving Fe because, as pointed out at the end of section 5.9, these plots differentiate between the distributions of achondrites and mesosideritic silicate fractions. In such plots, the trend of Binda's glassy microbreccias cuts across the basaltic achondrite trend and lies mainly in the mesosiderite field. The bulk analyses of Binda fall within the trend, indicating that the glassy phases are not genetically-unrelated materials transported from source areas of different composition by meteorite impact. Enrichment in Ca and Al relative to the bulk compositions of Binda, though less marked than in the howardites, suggests that modification of the original melts by selective fusion of plagioclase occurred. Confirmation of this may be found in the plot of the norms of the glassy microbreccias (Fig. 6.1), in which all the points are displaced towards the feldspar vertex.

7.4.14 The alkalis in the glassy phases, and their possible significance

The bulk analyses tabulated in Chap. 4 show that the weight ratio of Na:K in the basaltic achondrites is of the order of 10:1, although variation results from the difficulty of determining K in the low concentrations present. However, reference to the full set of averaged data on glassy phases in the five meteorites studied (Tables A3.33 - A3.41) shows that this ratio is not universal in these materials. Many analyses contain relatively large amounts of K_2O that exceed the Na_2O present. It is perhaps surprising that this feature has not received more attention. Anomalously high concentrations of K were observed in the glasses in Malvern at an early stage of the present investigation, and these were commented on also by JÉROME and DESNOYERS (1974). Three analyses of Malvern glass in Table 1 of NOONAN (1974) show abnormal contents of K, without comment or discussion; the same source lists analyses of glass from Bununu that display Na:K ratios typical of the basaltic achondrites. DESNOYERS and JÉROME (1977) briefly discussed the phenomenon in relation to Malvern and expressed the view, without offering an alternative, that selective volatilization does not provide a satisfactory explanation. Some consideration of the data of the present investigation is therefore appropriate in order to determine whether glassy phases in meteorites other than Malvern show anomalous contents of K and to try to suggest a possible explanation.

Table 7.6 summarizes the distribution of glassy fragments analyzed in this study that have anomalous Na/K ratios. Of the 237 glassy clasts analyzed (Table 1.2), 73 contain anomalously high concentrations of K. The majority of these are clasts of 'true' glass in Malvern, but some of the glassy microbreccias also are anomalous. Further examples occur in the glasses of Bununu and Molteno, but not in the glassy microbreccias.

Table 7.6. Distribution of fragments with approximately achondritic values for the Na/K (wt) ratio ('low K') versus those with abnormal values ('high K') in the various types of glasses analyzed

METEORITE	Glasses		Glassy microbreccias		Devitrified glasses	
	Low K	High K	Low K	High K	Low K	High K
Binda	--	--	9	0	--	--
Bununu	10	1	11	0	--	--
Frankfort	--	--	1	0	--	--
Malvern	7	51	60	9	14	0
Molteno	25	12	27	0	--	--

The analytical data on the anomalous phases (tabulated in full in the appendices) indicates that, in relation to glasses with achondritic Na/K ratios, their contents of Na are low whereas the concentration of K may be greater by an order of magnitude. Selective volatilization during formation of the glasses may be invoked to explain the low Na concentrations, but it cannot account for the enhancement of K in glasses that, apart from the alkalis, are compositionally similar to their counterparts with achondritic levels of these elements. Consequently, in the absence of a mechanism for increasing the absolute amounts of K in these atypical glasses (Table 7.6), it appears reasonable to suppose the glasses are of exotic origin and represent melts of source materials with alkali contents different from the sources that produced the achondrites and the majority of the glasses encountered in this investigation. To approach the problem from the opposite direction, i.e. to consider that the achondritic sources were depleted in K relative to the sources of the anomalous glasses, does not provide a solution, for in that case some means of enhancing the Na content of the achondritic source materials must be found.

The existence of glasses of exotic origin - implicit in the interrelationships of the major elements - was discussed above (see (4) and (5), section 7.4.13). An attempt was made to correlate these glasses, whose plotted positions generally lie on the Ca-, Al-poor side of the composition of the host meteorite, with the glassy phases that have anomalous Na/K ratios. This approach, which used both compositional and petrographic data, was not wholly successful. In Bununu, the only glass that consistently plots in a position relative to the bulk composition of the howardite that suggests it may be of exotic origin is also the only glassy component with an anomalous Na/K ratio. Unfortunately, this positive result cannot be claimed for Malvern and Molteno, despite careful study of the data. At best, it may be said that a slight tendency towards correlation exists in the Malvern glassy bodies, but that even this was not observed in their counterparts in Molteno. In Molteno the anomalous alkali ratios occur mainly in glasses that are redder than the others, a minor difference that may, nevertheless, suggest a different origin. However, the lack of positive proof of the correlation sought does not negate the reasoning that glassy clasts with anomalous concentrations of Na and K represent contributions to howarditic breccias from an external, but related, source. Such a source might be found in late-stage immiscible liquids produced by fractionation of eucritic, or more magnesian, melts generated by partial melting of the achondritic source region (section 5.10.2 and Chap. 9). Support for the existence of late-stage liquids comes from the presence, in the howardites, of rare glass clasts with highly siliceous compositions.

CHAPTER 8

COMPUTER MODELLING OF EUCRITE GENESIS

To err is human; to really foul
things up requires a computer.

Bill Vaughan (reported in
'Bartlett's Unfamiliar
Quotations', 1972)

8.1 INTRODUCTION

Although the emphasis in the present investigation falls chiefly on the genesis of the howardites, the scope of the study (as defined in Chap. 1) includes also aspects of the origin and evolution of eucrites and diogenites. Attention has been given to the chemical relationships between these classes of achondrites and to evaluating the probability of a genetic link between achondrites and the silicate portions of mesosiderites (see Chap. 5). In the last few years, great interest has focused on the origin of the eucrites and on the nature of the eucrite parent body, which may well be the source region for the other achondrite classes and perhaps even the mesosiderites. The important work of STOLPER (1975a, 1975b, 1977a) raised questions of interest to the present investigation and prompted the application of the available bulk chemical data to an approach involving computer modelling in the hope that this technique would provide partial answers to these questions.

Some of the material on which this chapter is based has been extracted from a paper (SIMPSON and AHRENS, 1979) published in Meteoritics, Vol. 14, No. 2, June 30, 1979. The present writer was responsible for all

the material from that paper that is used in this chapter.

8.2 PREVIOUS WORK ON EUCRITE GENESIS

STOLPER (1977a) proposed that melts of eucritic composition were the first to be produced in the early melting and differentiation of the basaltic achondrite parent body, and that the Mg-rich pyroxenes present in howardites, diogenites, and mesosiderites crystallized from magnesian liquids generated by further partial melting of the residues of the source materials after these materials had been exhausted of plagioclase. He further postulated that the cumulate eucrites Moore County, Moama, and Serra de Magé did not originate by crystal accumulation from the 'primary' eucritic melts, e.g. Juvinas and Sioux County, but were derived by advanced fractionation of the later, more magnesian melts. This two-stage model of eucrite genesis was necessitated by his calculations that the pyroxenes in cumulate eucrites equilibrated with residual liquids more Fe-rich than any known eucritic compositions. Stolper does state, however, that liquids similar in composition to the Fe-rich eucrites Nuevo Laredo and Lakangaon could have been produced by fairly extensive fractionation (about 40%) of plagioclase and pigeonite from the 'primary' eucritic melts.

The situation produced by this reasoning is rather unsatisfactory, even when the incomplete nature of the meteorite record is taken into account. On the one hand are the cumulate eucrites - Moore County, Moama, and Serra de Magé - for which no residual liquids can be identified, while on the other hand the Fe-rich residuals from the fractionation of 'primary' eucrites such as Juvinas and Sioux County appear to have no corresponding cumulates. CONSOLMAGNO and DRAKE (1977) studied this problem by means of quantitative computer modelling of the REE contents of the eucrites concerned, and concluded that Moore County and Serra de Magé could have been derived from a

Juvinas-like liquid by fractional crystallization of plagioclase and pigeonite, and that the residual liquids had compositions similar to that of Nuevo Laredo at the stage at which about 30% of the original liquid had crystallized. In effect, therefore, Consolmagno and Drake postulated a single-stage origin for the majority of eucrites (the exceptions being Stannern and Ibitira) by fractionation of the eucrites designated as primary melts by STOLPER (1977a), as distinct from the more complex two-stage process originally proposed by him.

8.3 THE COMPUTER MODELLING

Because of the importance of eucrite genesis to the current project and the strong indications that have emerged from virtually every relationship examined involving chemical or normative data that the eucrites (with a few exceptions) constitute a single differentiation series, an attempt was made to test these alternative models by quantitative computer modelling using published analyses of non-cumulate and cumulate eucrites from Table 4.7. This approach involved major and trace element concentrations, and was therefore more broadly based than the study of CONSOLMAGNO and DRAKE (1977). Another investigation that used Zr, Sc, Ba, Sr, and Y to model eucrite genesis (REID et al., 1979) reached essentially the same conclusions as the present study, and is considered in Chap. 9.

8.3.1 Method

Computer modelling techniques are routinely employed in the Department of Geochemistry at U.C.T. in the study of igneous fractionation and partial melting processes. A full account of these techniques and their theoretical background is to be found in LE ROEX (1980) and will not be repeated here. In outline, the procedure was as follows: a departmental program

written by A.R. Duncan based on the least squares linear mixing technique of BRYAN et al. (1969) was used to estimate the major element compositions of the products of fractional crystallization of 'primary' eucritic liquids. These major element approximations were checked with published trace element data that are, unfortunately, rather scanty for some of the meteorites studied. The trace element estimates were calculated, assuming surface equilibrium, using the equation of GREENLAND (1970) for phases crystallizing in constant proportions with constant distribution coefficients. Trace elements used include both 'incompatible' types, with distribution coefficients approaching zero for the fractionating minerals, and a 'compatible' element, Sr, which has a distribution coefficient for plagioclase well in excess of unity.

8.3.2 Results

Although the possibilities of this mode of investigation were not exhaustively explored, the results of trials were promising, as the example given in this chapter indicates. The results of this particular application of computer modelling are set out in Tables 8.1 and 8.2. The distribution coefficients used, which were taken from a compilation by LE ROEX (1980), appear in Table 8.3. The major element calculations (Table 8.1) have, as a starting point, a liquid with the composition of Sioux County, which STOLPER (1977a) regarded as one of the 'primary' eucritic melts from which the other 'liquid' eucrites could have been generated by fractional crystallization. These calculations show that subtraction of an assemblage (conveniently referred to as a 'mix') of pigeonite, plagioclase, chromite, and metallic Fe yields a residual liquid similar to Nuevo Laredo at a stage corresponding to 32% crystallization of the initial liquid. This figure is in agreement with the estimate of 30-40% crystallization made by STOLPER (1977a) on the basis

of the Zr concentrations in these meteorites, and with the value of 30% solidification calculated by CONSOLMAGNO and DRAKE (1977).

The compositions of the mineral phases used in the successful 'mix' (Table 8.1) closely approximate those reported from the cumulate eucrite Moama (LOVERING, 1975) except for chromite, the analysis of which contains too much TiO_2 , presumably because of intergrown ilmenite. Consequently, an analysis of a purer chromite from the achondrite Binda (BICRO3, Table A3.1) was substituted, normalized to 100% in accordance with all the compositional input data of Table 8.1. Recalculation of the modal analysis of Moama (LOVERING, 1975) to weight percentages shows a close correspondence to the proportions of the fractionating minerals in the 'mix'. The ratio of pigeonite to plagioclase (57:43) calculated for the 'mix' is also in good agreement with the proportions of these minerals (60:40) estimated from the results of experimental petrology (STOLPER, 1977a) to be present in the 'primary' eucritic liquids produced by equilibrium partial melting of the source region of the eucrite parent body.

The trace element estimates were calculated for 'parent' (Sioux County) and 'daughter' (Nuevo Laredo) compositions at the degree of crystallization (32%) indicated by modelling of the major elements. They therefore constitute a check on the validity of that modelling. Table 8.2 shows that good agreement exists between the values observed in the selected suite of trace elements in Nuevo Laredo and those predicted by calculation from the concentrations recorded in Sioux County. The trace element check is therefore satisfactory, and serves to strengthen the validity of conclusions drawn from the major element modelling.

Table 8.1. Least squares approximation to a residual liquid (Nuevo Laredo) derived by subtraction of cumulate phases, similar to Moama in compositions and proportions, from an original eucritic magma (Sioux County)

INPUT DATA						
	Sioux County	Plagio- clase	Pigeon- ite	Chromite (BICR03)	Metal	Nuevo Laredo
SiO ₂	49.06	44.67	51.76	0.00	0.00	49.65
TiO ₂	0.62	0.00	0.10	1.91	0.00	0.95
Al ₂ O ₃	12.86	35.51	0.47	10.89	0.00	11.82
Cr ₂ O ₃	0.35	0.00	0.27	52.65	0.00	0.29
FeO*	18.59	0.09	24.02	31.65	100.00	20.18
MnO	0.56	0.00	0.90	0.34	0.00	0.56
MgO	7.11	0.08	18.69	2.55	0.00	5.48
CaO	10.38	19.12	3.80	0.00	0.00	10.44
Na ₂ O	0.44	0.50	0.00	0.00	0.00	0.57
K ₂ O	0.04	0.02	0.00	0.00	0.00	0.05

CALCULATED RESULTS FOR NUEVO LAREDO								
Major Elements				'Mix'		Recalculated (Wt %)		
	Obs.	Calc.	Diff.					
					Wt %	S.D.	Cumulate	Moama
SiO ₂	49.65	49.67	0.02					
TiO ₂	0.95	0.87	-0.08	Sioux County	146.81	1.11		
Al ₂ O ₃	11.82	11.80	-0.02	Plag.	-19.50	0.47	41.7	43.6
Cr ₂ O ₃	0.29	0.30	0.01	Pig.	-26.36	0.65	56.3	54.4
FeO*	20.18	20.19	0.01	Chr.	-0.27	0.09	0.6	1.6
MnO	0.56	0.58	0.02	Metal	-0.67	0.09	1.4	0.4
MgO	5.48	5.49	0.01					
CaO	10.44	10.51	0.07	TOTAL	100.01	1.37	100.0	100.0
Na ₂ O	0.57	0.55	-0.02					
K ₂ O	0.05	0.05	-0.00					

Sum of Squares of
Differences = 0.01

- Notes:
1. For the least squares approximation to be acceptable, the sum of the squares of the differences should not exceed 0.10.
 2. S.D. - standard deviation
 3. Sources of the recalculated analyses used:
 Sioux County - McCarthy (1971)
 Nuevo Laredo - Duke and Silver (1967)
 4. The mode of Moama is recalculated from that given by Lovering (1975).

Table 8.2. Trace element check on the validity of the major element modelling presented in Table 8.1. All concentrations are in ppm unless otherwise stated.

	SIOUX COUNTY		NUEVO LAREDO		
	Obs.	Ref.	Obs.	Ref.	Calc.
Li	8.88	1	12.4	1	13.0
Sc	28	2	38	2	36
Rb	0.205	1	0.324	1	0.300
Sr	75.7	1	80.5	1	83.0
Zr	48	3	67	4	66
Cs	9.2 ppb	1	13.8 ppb	1	13.5 ppb
Ba	27.2	1	39.3	1	39.7

- References:
- 1 Tera et al. (1970)
 - 2 Schmitt et al. (1972)
 - 3 von Michaelis et al. (1969)
 - 4 Schmitt et al. (1964)

Table 8.3. Distribution coefficients used in the present study (from a compilation by Le Roex (1980))

	Li	Sc	Rb	Sr	Zr	Cs	Ba
Plagioclase	0.01*	0.065 ¹	0.026 ³	1.83 ³	0.01*	0.001*	0.054 ³
Pigeonite	0.01*	0.53 ¹	0.0003 ³	0.0019 ³	0.3*	0.001*	0.0004 ³
Chromite		0.048 ²					

- References:
- 1 Lindstrom (1976)
 - 2 Nagasawa et al. (1976)
 - 3 Philpotts and Schnetzler (1970)
- * Assumed value

8.4 DISCUSSION

As pointed out by CONSOLMAGNO and DRAKE (1977), the possible presence of minor phases such as spinel and metal can complicate quantitative modelling of cumulates, especially in respect of the abundances of trace elements such as Sc and Cr. For this reason, chromite and metallic Fe (Lovering's analyses showed that the metal in Moama is virtually devoid of Ni) were included as discrete fractionating phases in the major element mixing calculations. Table 8.1 shows that acceptable least squares approximations, as judged by the residual differences between observed and calculated values in Nuevo Laredo, were obtained for Fe, Mg, and Cr, Cr being treated as a major element in this instance. In the trace element check calculations, the estimation of Sc in the residual liquid was also considered satisfactory. These calculations showed that the presence of chromite and metallic Fe as fractionating phases has only a negligible effect on the concentration of Sc in the final liquid. No coefficient for the partitioning of Sc between the liquid

phase and metallic Fe appears in Table 8.3, but it can be shown that such a coefficient would have to have a value of about 7.0 in order to lower the estimated concentration of Sc by as little as 1 ppm, which would not invalidate the check calculation.

The reservation expressed by CONSOLMAGNO and DRAKE (1977) concerning the possible effect of spinel and metal on their quantitative model was largely prompted by criticism from M.-S. Ma and R.A. Schmitt, of the Corvallis (Oregon) research group, who suggested that the simple REE model would not "predict abundances of Sc, Cr, Na and Ba, or Fe/(Fe+Mg) ratios which are consistent with observed values for Serra de Magé and Moore County" (CONSOLMAGNO and DRAKE, 1977, p. 1276). This objection was briefly stated by MA et al. (1977) in a study of the unique achondrite Angra dos Reis in which the modeling technique used failed, within the framework of the assumptions made, to derive a genetic link between 'primary' eucritic magmas and Moore County, based on the observed abundances of Ba, Sr, REE, and Sc. This conclusion, and the criticism of the Consolmagno and Drake model, were repeated without further elaboration in another paper from the same group (FUKUOKA et al., 1977). However, while maintaining their original objection, MA and SCHMITT (1979) conceded that the STOLPER (1977a) model for the origin of the cumulate eucrites also may not stand up to testing by REE data. This conclusion was reinforced by their calculations involving La, Sm, and the Sm/Eu ratio. These calculations suggested that Serra de Magé and Moore County are not related to one another, as Stolper claims, by fractional crystallization of diogenitic orthopyroxene from a liquid produced by extensive melting of the plagioclase-free source material residual in the source area after removal of the melts that produced the non-cumulate eucrites.

More direct support for the Consolmagno and Drake model came from a further study of REE abundances in the cumulate eucrites, particularly

Moama (HAMET et al., 1978). These authors confirmed that Moama could have been derived from a liquid similar to Sioux County by 20-30% fractional crystallization of pigeonite and plagioclase in peritectic proportions but with differential rates of accumulation. Alternatively, 1-5% fractional crystallization of these phases from a Juvinas-like liquid would have had the same result. Hamet and his co-workers concluded that Moama, Serra de Magé, and Moore County were probably formed in a single differentiation event.

Although I am not aware of any direct criticism of the published computer modelling on which this chapter is based (SIMPSON and AHRENS, 1979), the fact that the computer treatment produced results that support the conclusions of CONSOLMAGNO and DRAKE (1977) renders it indirectly subject to the objections raised by the Corvallis group. This has prompted an examination of the bases for these objections. The concentrations of those elements that are claimed to be inconsistent with a simple, one-stage fractional crystallization model of eucrite genesis are listed, together with the corresponding Fe/Fe+Mg ratios, for the eucrites involved in the modelling reported in this chapter and, additionally, for Moore County and Serra de Magé (Table 8.4). Where possible, two values have been included for each meteorite, the first taken from the data used in the present study, the second from the data compilation of SCHMITT et al. (1972) on which the criticisms to be answered are presumably based.

In Table 8.4, the five eucrites concerned are arranged in sequence according to their Fe/Fe+Mg ratios in order to reveal whether variations in element concentrations are systematically related to variation in that ratio, i.e. to differentiation. Unfortunately, some data are lacking for Moama, but the tabulation shows clearly that there is a coherent relationship between the element concentrations used in the present study and the Fe/Fe+Mg ratios in the eucrites; e.g. the steady increase in Cr_2O_3 from Nuevo Laredo to Moama

is matched by a regular decrease in Fe/Fe+Mg ratio. This is not true for the critical data on Na and Cr taken from SCHMITT et al. (1972), which shows no such regularity. Moreover, re-determination of the Na₂O value for Serra de Magé (MA and SCHMITT, 1979) gave a lower figure (0.273%) which improves the trend in the data of the present investigation but fails to establish regularity of variation in the original Na data of the Schmitt group. Similarly, substitution of the re-determined concentration of 0.544% Cr₂O₃ - which is identical to that used in the current study (Table 4.7) - does not systematize the pattern of variation of the Schmitt data on Cr in Table 8.4. The concentrations of Sc determined by SCHMITT et al. (1972) are, however, consistent with a single-stage fractional crystallization model as proposed by CONSOLMAGNO and DRAKE (1977) and by the present writer. The progressive increase in Sc with increasing Fe/Fe+Mg ratio is to be expected from the higher proportion of Ca-rich pyroxene present in later differentiates; the distribution coefficient for this element in sub-calcic pyroxenes of basaltic rocks is 0.53 (LINDSTROM, 1976), but increases to about 3.0 in calcic pyroxenes (DALE and HENDERSON, 1972; ONUMA et al., 1968). The Ba values of the present study show the expected variation; the element is virtually incompatible with respect to pyroxenes, but tends towards increased concentration in feldspar as differentiation proceeds (KORRINGA and NOBLE, 1971).

In summary, therefore, comparison of the sets of data presented in Table 8.4 suggests that the objections of the Corvallis group to a single-stage model for the derivation of cumulate eucrites from melts similar to Sioux County appear to lack foundation if they are based on the data of SCHMITT et al. (1972). Some of these data (e.g. Sc) actually point strongly to the genetic link between the different types of eucrites proposed by CONSOLMAGNO and DRAKE (1977), HAMET et al. (1978), SIMPSON and AHRENS (1979), and the present work. The difficulty, as admitted by FUKUOKA et al. (1977),

Table 8.4. A comparison of Fe/Fe+Mg ratios and concentrations of Na, Cr, Sc, and Ba in a series of eucritic meteorites that are probably genetically related

Meteorite	Fe/Fe+Mg (molar)	Na ₂ O (Wt %)	Na* (ppm)	Cr ₂ O ₃ (Wt %)	Cr* (ppm)	Sc* (ppm)	Ba (ppm)
Nuevo Laredo	0.674	0.57	3430 ± 70	0.29	1810 ± 100	38 ± 2	39.3
Sioux County	0.595	0.44	2823 (ave.)	0.35	2187 (ave.)	28 ± 1	27.2
Moore County	0.507	0.414*	3070 ± 60	0.44	1930 ± 100	24 ± 1	18.6
Serra de Magé	0.444	0.456*	3380 ± 70	0.54	1740 ± 40	14 ± 1	14
Moama	0.412	0.22	---	0.61	---	---	---

Notes: 1. Fe/Fe+Mg ratios are taken from Table 5.9.

2. Values marked * are taken from Schmitt et al. (1972).

3. All other values are taken from Table 4.7.

4. Ma and Schmitt (1979) give the following values for Serra de Magé: Na₂O 0.273%

Cr₂O₃ 0.544%

Sc 16 ± 1 ppm

5. Ba values are taken from Tera et al. (1970), except for Serra de Magé (Ma and Schmitt, 1979).

may be that the very small samples analyzed by neutron activation techniques are not truly representative of the heterogeneous brecciated meteorites from which they were taken. It is also possible that such unrepresentative sampling may not affect all the elements to the same degree so that some enrichment trends, e.g. that of Sc, may be discernible although the absolute values may lack accuracy.

The possibility that the criticisms of the Corvallis group may have been based on unsatisfactory data does not affect the other main objection to the proposed single-stage model, viz. the contention of STOLPER (1977a) that the pyroxenes of the cumulate eucrites could have equilibrated only with liquids richer in Fe than Nuevo Laredo and Lakangaon. This, if valid, imposes a serious constraint on the formation of cumulate eucrites, and has therefore been examined in some detail. Stolper based his calculations on a pigeonite-liquid distribution coefficient for Fe/Mg of 0.30, the average determined from a series of 1 atm quenching experiments on Juvinas and Sioux County. This coefficient is obviously the critical factor in the constraint and, as far as can be judged from the microprobe data published (Stolper's Table 2), has been correctly determined. An independent check on the coefficient was made using the technique of GROVE and BENCE (1977), who studied experimentally pyroxene-liquid interaction in the quartz-normative lunar basalt 15597. This basalt is broadly similar in composition to eucrites such as Juvinas and Sioux County. The equation used to determine the distribution coefficient $K_D^{Fe/Mg}$ for low-Ca clinopyroxene is as follows:

$$\log K_D^{Fe/Mg} = -2.08 \left(\frac{10^3}{T, ^\circ K} \right) + 0.89$$

In all four of the Juvinas and Sioux County experiments for which the $K_D^{Fe/Mg}$ could be calculated, pigeonite crystallized at 1171°C (STOLPER,

1977a, Table 1). This gives a $K_D^{Fe/Mg}$ of 0.28, which is in good agreement with Stolper's value if the compositional difference is taken into account. Furthermore, the established temperature dependence of Fe-Mg partitioning between low-Ca clinopyroxene and liquid acts in favour of the Stolper model by lowering the Fe/Mg distribution coefficient, and this in turn raises the Fe/Fe+Mg ratio of the residual liquid with which the pyroxene is in equilibrium. The magnitude of the drop in $K_D^{Fe/Mg}$ has been shown in the study of GROVE and BENCE (1977) to be from 0.28 at 1200°C to 0.17 at 975°C, resulting in an increase of the Fe/Fe+Mg ratio of the equilibrium liquid to 0.81, far above the values of known eucritic melts.

Against these arguments, however, are ranged several factors that may affect the validity of the value of 0.30 for the $K_D^{Fe/Mg}$ governing partitioning between pigeonite and liquid. This value, as noted above, is critical for the Stolper model for the formation of cumulate eucrites. Stolper's own original caution must be included among these factors. He stressed that if the pigeonites in these cumulates had altered compositionally (by subsolidus equilibration or reaction with intercumulus liquid) from the state in which they originally crystallized, his calculation of the Fe/Fe+Mg ratios of the liquids in equilibrium with them would be rendered invalid. The petrographic or chemical evidence that might resolve this uncertainty is not available to me, but this important check ought to be carried out at some future date.

The next factor is observational, based on the present investigation. In Chap. 5 of this thesis, inter-element relationships in the bulk compositional data from 42 achondrites and mesosiderites were thoroughly examined, as evidenced by many plots. In addition, the behaviour of major, minor, and trace elements in relation to the Fe/Fe+Mg ratio or its converse, the Mg/Mg+Fe ratio, which were used as indicators of the progress of frac-

tional crystallization or partial melting, was studied. In each of these plots, a calculated regression line could be drawn through all, or almost all, of the eucrites included in the study for which data were available. These regression lines define evolutionary trends distinct from those of the other achondrites and the mesosiderites, and establish the eucrites as a separate series. The regression lines are, of course, subject to the quality of the data, but the fact that a good 'fit' can be obtained for cumulate and non-cumulate eucrites irrespective of the elements or element ratios involved is a clear indication that these meteorites are related by a simple igneous process, or set of processes. The inter-element relationships presented in the current investigation therefore constitute a body of evidence strongly in favour of the single-stage formation of cumulate eucrites advocated by the computer modelling of CONSOLMAGNO and DRAKE (1977) and of the present study. The desirability of finding some means of reconciling the experimental data with the observational evidence obtained from the meteorites themselves is obvious, and the chief obstacle to this remains the $K_D^{Fe/Mg}$ of 0.30 experimentally determined by STOLPER (1977a).

The values of distribution coefficients may be affected not only by temperature, as considered above, but also by composition. Stolper recognized that his experimentally-determined Fe/Mg distribution coefficients for pigeonite-liquid and olivine-liquid were greater than their lunar equivalents, and ascribed the difference to the lower content of TiO_2 in eucrites compared to lunar basalts. This difference was quantified by LONGHI et al. (1978), who extended the work of ROEDER and EMSLIE (1970) on olivine-liquid equilibrium in terrestrial rocks to lunar basaltic liquids produced by equilibrium partial melting. They found that the $K_D^{Fe/Mg}$ for olivine-liquid is 0.33 for low-Ti lunar basalts as opposed to 0.28 in the high-Ti counterparts; Stolper's value for eucrites is 0.35. Comparable figures for the more complex parti-

tioning of Fe and Mg between pigeonite and liquid are not available, but the work of Longhi and his colleagues, which has shown the compositional effect to be dependent on changes in the structure of the liquid, suggests that the $K_D^{Fe/Mg}$ for pigeonite-liquid would be at least similarly affected, if not to a greater extent (cf. its temperature-dependence in contrast to the lack of response of the olivine-liquid coefficient to temperature change). It is therefore possible for the value of 0.30 for the pigeonite-liquid distribution coefficient to have changed during the course of fractional crystallization as a result of substantial changes in the composition of the residual liquid. Although this argument must remain somewhat speculative because of the lack of appropriate data on low-Ca pyroxenes, it serves as a reminder that compositional change is a factor in Fe-Mg partitioning that may cast some doubt on calculations based on constant distribution coefficients.

A further complicating factor has emerged from recent experimental work on the crystallization kinetics of multiply saturated basaltic magma, and is therefore relevant to problems of eucrite genesis (GROVE and BENCE, 1979). The study was carried out on a Luna 24 ferrobalt that is compositionally very similar to Sioux County (GROVE and VANIMAN, 1978), and showed that partitioning of Ca, Fe, and Mg in clinopyroxene-liquid systems departs from equilibrium at rapid ($>40^\circ\text{C/hr}$) rates of cooling. When this occurs, the distribution coefficients for these elements approach unity as, consequently, does the value of the exchange distribution coefficient $K_D^{Fe/Mg}$. WALKER et al. (1978) showed that rapid cooling rates did operate in the crystallization of at least some eucritic materials. They inferred from the sizes of plagioclase crystals in clasts in Stannern that the range of cooling rates represented was from about 0.1 to 100°C/hr , and calculated that this entire cooling range could have been experienced in the outermost three metres of a small magma body. The possibility of disequilibrium occurring

at rapid rates of cooling allows more latitude in the mechanism of formation of the cumulate eucrites than the Stolper model, which, as discussed earlier, does not seem to be supported by the current study of inter-element relationships. Some possible ways of forming eucritic cumulates that are now open as a result of the demonstration by GROVE and BENCE (1979) that equilibrium may not have prevailed during the entire course of crystallization of a basaltic magma will now be considered.

The first possibility is that of slow cooling of a 'primary' eucritic melt compositionally similar to Juvinas or Sioux County, probably in a plutonic environment. Such crystallization proceeded under equilibrium conditions with Fe-Mg partitioning governed by the $K_D^{Fe/Mg}$ of 0.30 experimentally determined by STOLPER (1977a). The pyroxenes in the earliest pyroxene-plagioclase cumulates to form had Fe/Fe+Mg ratios of 0.31, corresponding to the most magnesian pigeonite reported in Stolper's Table 2 (Juvinas run 14: molar proportions $En_{66}Fs_{30}Wo_4$). The Fe/Fe+Mg ratio (molar) of the liquid with which these pyroxenes were in equilibrium was, predictably, 0.60 - that of Juvinas or Sioux County (see Table 5.9 and Stolper's Table 4). Such equilibrium crystallization could have produced pyroxene-plagioclase cumulates until the Fe/Fe+Mg ratio of the pyroxenes reached 0.40, at which point the residual equilibrium liquid would have attained a ratio of 0.69, equal to that of Lakangaon, the most Fe-rich eucrite known. (It may be appropriate here to observe how all hypothetical reasoning in meteorites is limited by the imperfect and probably completely unrepresentative sampling available to us.) The upper limit of the compositional range of pyroxenes possible in cumulate eucrites formed under equilibrium conditions is therefore about $En_{55}Fs_{38}Wo_7$, if the 'known eucrite' constraint is applied.

Further possibilities of cumulate formation result from disruption of this tranquil scenario of equilibrium crystallization, which could have

occurred at any point in the pyroxene-plagioclase fractionation sequence. The disruption could have taken place at different stages of crystallization in different reservoirs of 'primary' melt. Some or all of the residual liquid may have been erupted on to the surface of the parent body, or intruded into a higher level of the crust. More rapid cooling rates prevailed in both of these situations but, if the residual eucritic melts had low viscosities comparable to those of the lunar basalts, crystal settling and cumulate formation would have been possible. With the disequilibrium conditions attendant on rapid cooling (GROVE and BENCE, 1979), the equilibrium $K_D^{Fe/Mg}$ of 0.30 no longer applied. Instead, higher values prevailed, depending on the degree of disequilibrium present. The residual liquids, separated from the original cumulates and erupted or intruded into cooler surroundings, were still sufficiently magnesian (Fe/Fe+Mg ratios in the range 0.60 - 0.69) to crystallize the pigeonites observed in the cumulate eucrites with only relatively minor increases in the value of $K_D^{Fe/Mg}$, i.e. far below unity. Thus a further range of cumulates, with pigeonites more ferriferous than those in the cumulates formed under equilibrium conditions, is possible provided that rapid cooling rates were established in the later part of the crystallization history of the 'primary' eucritic melt.

Some quantification of this hypothetical two-stage cooling history, proposed to account for the observational data contained in Chap. 5 on the relationships between cumulate and non-cumulate eucrites, is presented in Table 8.5. Fe/Fe+Mg ratios are summarized for conditions of equilibrium crystallization, calculated from the data of Tables 2 and 3 of STOLPER (1977a). For disequilibrium conditions resulting from rapid cooling, the increased values of $K_D^{Fe/Mg}$ in clinopyroxenes that are required to match the Fe/Fe+Mg ratios of pigeonites in Moama, Serra de Magé, and Moore County (Stolper, Table 4) with the meteorites Nuevo Laredo and Lakangaon, regarded

Table 8.5. The upper part of this table shows the range of Fe/Fe+Mg ratios in pigeonites, crystallized from a Juvinas-like melt, that can be in equilibrium with residual liquids corresponding to known eucrites, assuming a pigeonite-liquid distribution coefficient for Fe/Mg of 0.30. The lower part lists the distribution coefficients required for the production, under conditions of rapid cooling and disequilibrium (Grove and Bence, 1979), of residual liquids corresponding to Nuevo Laredo and Lakangaon by subtraction of cumulates whose pigeonites have Fe/Fe+Mg ratios similar to those of the pyroxenes in cumulate eucrites.

Meteorite	Fe/Fe+Mg (pigeonite)	K_D Fe/Mg pige.	Fe/Fe+Mg (residual liquid)	Meteorite corresponding to residual liquid
SLOW COOLING, EQUILIBRIUM				
(Juvinas experiment) ¹	0.31 ¹	0.30 ¹	0.60 ²	(Juvinas, Sioux County
(Juvinas experiment) ¹	0.40 ²	0.30 ¹	0.69 ³	Lakangaon
RAPID COOLING, DISEQUILIBRIUM				
Moama	0.42 ¹	0.36 ²	0.67 ³	Nuevo Laredo
Moama	0.42 ¹	0.33 ²	0.69 ³	Lakangaon
Serra de Magé	0.44 ^{1*}	0.39 ²	0.67 ³	Nuevo Laredo
Serra de Magé	0.44 ^{1*}	0.35 ²	0.69 ³	Lakangaon
Moore County	0.50 ^{1*}	0.49 ²	0.67 ³	Nuevo Laredo
Moore County	0.50 ^{1*}	0.45 ²	0.69 ³	Lakangaon

Sources of data: 1 Stolper (1977a)

2 Calculated

3 Table 5.9, this work

* Based on refractive indices (Duke and Silver, 1967)

here as their corresponding residual liquids, are listed. It will be seen that the required increase in $K_D^{Fe/Mg}$ is very small for the Moama-Nuevo Laredo pair that is the subject of the computer modelling described in this chapter. The largest increase is necessary for Moore County, but even the values for this cumulate fall far below the $K_D^{Fe/Mg} = 1$ reported by GROVE and BENCE (1979) for a cooling rate of 150°C/hr . It is appreciated that this approach is speculative, as the very definition of distribution coefficients implies the maintenance of equilibrium in the crystallizing system. Nevertheless, Table 8.5 represents an attempt to show how small the departure from equilibrium must be in order to accomplish the formation of cumulate eucrites by fractionation of a single source material, although a two-stage cooling history is involved.

The preceding arguments, though partly speculative in some instances, may serve to indicate that the $K_D^{Fe/Mg}$ of 0.30 for clinopyroxene-liquid partitioning - the basis of Stolper's contention that the cumulate eucrites cannot be derived directly from 'primary' eucritic melts - is subject to variation caused by changing temperature, compositional change, and increased cooling rates. Added to these factors is the observation that the inter-element relationships among eucrites suggest an origin less complicated than that proposed by STOLPER (1977a). A final, but significant, commentary on the genesis of eucrites is to be found in the experimental data of Stolper himself, and has been implicit in some of the preceding reasoning. He showed that 30-40% crystallization of 'primary' melts like Sioux County could produce experimental liquids compositionally similar to Nuevo Laredo and Lakangaon (STOLPER, 1977a, p. 601). The pyroxenes produced experimentally by this crystallization process are shown in his Fig. 4 (p. 593). The earliest to crystallize has the composition $\text{En}_{66}\text{Fs}_{30}\text{Wo}_4$ (see earlier), while the most Fe-rich are very similar to the pigeonites in Moore County (DUKE and

SILVER, 1967)), i.e. the compositional range shown by these pyroxenes is greater, with compositions far more magnesian, than the pyroxenes of the cumulate eucrites. This range can, in fact, account for the most magnesian pigeonites observed in howardites and mesosiderites (POWELL, 1971; HEWINS, 1979b). Furthermore, the melting experiments on Sioux County and Juvinas compositions produced residual liquids far richer in Fe than Nuevo Laredo and Lakangaon. This suggests that similar meteorites may exist, but have not been found. The most Fe-rich liquids result from about 65% crystallization of the 'primary' melts (see Stolper's Fig. 9). This estimate is lower than that of CONSOLMAGNO and DRAKE (1977) in their modelling of the genesis of Moore County, but the Fe/Fe+Mg ratios of these liquids lie in the region of 0.77, which is the value calculated by Stolper (his Table 4) for the residual liquid in equilibrium with the pigeonites in that meteorite. Similarly, other experimental liquids produced by about 51% crystallization have Fe/Fe+Mg ratios of 0.72 (Stolper's Fig. 9); the figure of 50% was estimated by Consolmagno and Drake for Serra de Magé, and the Fe/Fe+Mg ratio is an exact match for that calculated by Stolper in his Table 4. These data point very strongly to the feasibility of deriving all eucrites by fractional crystallization of 'primary' melts originally produced according to the model of STOLPER (1977a), and therefore to the validity of the single-stage model advocated by CONSOLMAGNO and DRAKE (1977) and the present writer. If the indications of these data are correct, no mechanisms need be invoked to alter the distribution coefficients controlling Fe-Mg partitioning between pyroxenes and liquid, but the constraint that the liquids residual from the formation of the cumulate eucrites should correspond compositionally to known eucrites must fall away.

CHAPTER 9

DISCUSSION AND SUMMARY OF CONCLUSIONS

I am not young enough to know everything.

James M. Barrie (1860-1937)

9.1 INTRODUCTION

Throughout this report, interpretation of both new and previously published observations has been made and the significance of the results has been discussed. Conclusions - some firm, others of a more tentative nature - have been stated in the appropriate places in the text. It is the purpose of this chapter to assemble these conclusions in a form that is concise in relation to the wide scope of the project and the large amount of data collected in its execution, and to use them to formulate a hypothetical model of the genesis of the major classes of achondrites and their relationship to the mesosiderites. Additional discussion is included where necessary in comparison of this model with genetic schemes presented by other workers.

The chapter consists of three parts. In the first, conclusions on the relatively small-scale and near-surface processes that operated in the formation of the howardites and other achondrites are presented, and inferences are drawn on the physical conditions that prevailed during their formation. This section is based on evidence derived from the petrographic investigation (Chap. 3) and the microprobe analysis programme (Chap. 7) in the current project, and on published data on analogous meteorites and lunar rocks. The second part deals with conclusions reached on the formational processes in the outer mantle and crust of the achondrite parent body that produced the source materials of the achondrites. It relies largely on

observations and deductions based on the bulk chemical compositions of the achondrites and mesosiderites (Chap. 5), and on the computer modelling of eucrite genesis presented in Chap. 8. The third, and final, part of this chapter attempts to integrate all the evidence available from this investigation into a model for the formation of the achondrites that, in addition, suggests the existence and nature of a genetic relationship linking them with the mesosiderites.

9.2 THE FORMATION OF THE HOWARDITES

9.2.1 Introduction

Use of the data of this investigation to elucidate the mode of formation of the howardites was one of the main objectives of the project (section 1.2). Data resulting from the intensive study of Bununu, Frankfort, Malvern, and Molteno can be brought to bear on the problem; Binda has been shown not to be a howardite and is considered separately. The sections that follow summarize the conclusions reached on the physical and chemical attributes of the howardites, and a model for the formation of the howardites is presented that is based partly on the evidence of the present investigation and partly on the analogy of the formation of lunar breccias.

9.2.2 Physical and mineralogical aspects of the formation of the howardites

All four howardites studied are polymict breccias composed essentially of orthopyroxene, pigeonite, and calcic plagioclase, suggesting their derivation from at least similar source regions. All contain lithic clasts and glassy (or originally glassy) materials, but in widely varying amounts. They have been lithified and have suffered only very minor post-lithification fracturing and movement. Almost all the mineral and lithic components have undergone physical modification attributable to shock; clasts that do not

show shock effects are presumed to have been locally sheltered from the shock waves, e.g. in the 'lee' of larger clasts. Shock is inferred to have supplied the heat energy required for the local fusion of the heterogeneous regolith materials. Some of the resultant glasses were emplaced in the regolith in a plastic condition and intruded their surroundings, while others solidified prior to emplacement. Most of the glasses have incorporated mineral and, less commonly, lithic clasts and there is abundant chemical evidence (section 7.4) to show that the compositions of the glasses were generally modified by preferential assimilation of plagioclase inclusions. The rare metal grains in howardites are concentrated mainly in the glassy microbreccias, which were either formed in situ or emplaced in the breccia while still molten. This is interpreted to indicate derivation of the metal from impacting metal-rich projectiles that generated these glasses, a conclusion supported by the chemical evidence (section 7.3.3). No conclusive petrographic indications of the relative ages of the various types of glasses present in howardites were obtained from the study.

All howardites underwent a minimum of two impact events, or episodes during which impacts took place. The first produced the regolithic debris from which they were formed, and the second ejected them from the parent body. Additional minor impacts may generally have left no discernible record, but Malvern bears the imprint (in the form of the large eucritic microbreccia clast and its inclusions - section 3.3.2) of a further one, or possibly two, major brecciation events in its source region.

Metamorphic effects (other than lithification) are absent from the howardites examined. A small proportion of the lithic clasts, mainly pyroxene-plagioclase varieties, have been completely recrystallized, but these are regarded as exotic additions to the breccia from regions in which different thermal regimes prevailed. The few diagenetic clasts present exhibit

granoblastic textures and may therefore have been subjected to high temperatures. The complete lack of zonation in all the minerals, whether in separate clasts or occurring as components of lithic clasts, coupled with the common occurrence of uninverted pigeonite, indicates that material was contributed to the howardites from two different thermal environments - one of slow cooling, the other more rapid.

Correlated with the concept of two distinct cooling environments is the conclusion, based on crystal size and habit, that cumulate pyroxene-plagioclase rocks and orthopyroxene cumulates compositionally distinct from diogenites contributed more material to howardites than was previously realised. These sources, together with diogenites sensu stricto, presumably represent the slower cooling environments, whereas the series of eucritic melts and their differentiates, extruded at the surface of the parent body or intruded at shallow depths, constitute the more rapidly cooled source materials.

Physical and mineralogical factors therefore point to the conclusion that the formational processes for howardites were more complex than the simple mixing of eucritic and diogenitic source materials originally proposed by JÉROME and GOLES (1971). That the howardites were formed by mixing is not in dispute, and never was in the course of the present investigation. What did require definition was the nature of the materials from which these varied achondrites were derived. The following section sets out the main conclusions on this aspect of the problem arrived at from microprobe data on compositional variations in the constituent phases of the four howardites analyzed.

9.2.3 Compositional aspects of the formation of the howardites

One of the main aims of the study of the phase chemistry of the howardites was the search for evidence of compositional bimodality that

might indicate a binary mixture of chemically distinct end-members. This search was concentrated on the pyroxenes, and the results (sections 7.2.3 and 7.2.4) show conclusively that there is no bimodality in their distribution, particularly if a sufficiently large number of randomly-selected crystals in all modes of occurrence is analyzed. A suggestion of GOOLEY (1972) that howarditic chromites might show bimodality found no support from the data of this study (section 7.3.1). Bimodality was neither expected nor found in the plagioclases because of their rarity in diogenites.

The study of the phase chemistry of the howardites therefore produced no evidence in support of the two-component mixing model as originally stated (JÉROME and GOLES, 1971). On the contrary, the major components show continuous compositional variation in all four howardites examined. Pyroxene compositions extend from En_{86} to about En_{30} , the limit of the two-pyroxene field. Similar continuous ranges have been reported from other howardites, e.g. Kapoeta (FREDRIKSSON and KEIL, 1963; DYMEK et al., 1976) and Yamato 7308 (MIYAMOTO et al., 1978). The plagioclases also show variation in the range An_{75} to An_{96} (section 7.2.1) that can, moreover, be correlated with variations in the compositions of co-existing pigeonites in lithic clasts. From these data, it is concluded that howardites were formed from a regolith that contained fragments representative of a wide variety of source rocks, not merely the compositionally restricted eucrites and diogenites of the Jérôme and Goles mixing hypothesis. Furthermore, the regularity of the variation trends in pyroxenes and plagioclases, and their similarity to terrestrial analogues, point to the inescapable conclusion that the source materials were systematically related to one another by igneous processes - partial melting, or fractional crystallization, or a combination of both.

Pyroxenes and plagioclases included in glassy materials in the howardites show compositional ranges similar to those established for other

modes of occurrence; this is true even of the inclusions within individual glassy bodies of sufficient size to enclose a large enough sample of mineral clasts. This heterogeneity indicates that no re-equilibration of the included material took place, and confirms that no major post-formational heating of the howarditic breccias occurred, as was deduced petrographically from the absence of metamorphic effects.

Plagioclase is almost entirely restricted to the members of the eucrite series, the nature of which has been clearly established in other parts of the present investigation (Chaps 5 and 8). A study of plagioclase stoichiometry in the howardites (section 7.2.2) led to the conclusion that material contributed by the eucrite series represents a wide variety of cooling regimes. It was shown that, in general, a correlation exists in plagioclases in lithic clasts between textural indications of cooling rate, composition, and degree of departure from stoichiometry. The most sodic plagioclases occur in clasts whose textures suggest rapid cooling, and these feldspars show the greatest divergence from stoichiometry. Conversely, plagioclases that appear to have originated in slowly-cooled cumulates are highly calcic, with approximately stoichiometric compositions. These conclusions correspond with those of WEILL et al. (1970) and CRAWFORD (1973) on the petrogenesis of lunar basalts, and with the deduction in the preceding section, based on petrographic evidence, that the components of howarditic breccias indicate derivation from different cooling environments, even when the feldspars alone are considered.

Study of the variation in content of the minor elements Al, Ti, and Cr present in the pyroxenes of howardites (section 7.2.5) showed that variation trends exist that can be related to the crystallization trends defined by the major elements Ca, Mg, and Fe, as well as to changes in the crystal chemistry of the pyroxenes. An abrupt directional change in the Al-Ti-Cr

variation trend occurs, in all the howardites studied, at the point at which plagioclase appears in (or disappears from) the crystallization sequence and at which the dominant pyroxene changes from the ortho- to the clino- variety (or vice versa). This feature characterizes a break in the evolutionary sequence of the achondrites, the significance of which becomes more apparent below, when a hypothetical model for their genesis is presented.

The FeO/MnO (wt) ratios of the pyroxenes in all four howardites were found to define trends with slopes (≈ 35) identical to that of Kapoeta (DYMEK et al., 1976). Following Dymek and his co-workers, therefore, it is concluded that the source materials of howardites were formed in similar physico-chemical environments, and that these environments were different from those of lunar rocks, whose pyroxenes have ratios of about 60. Acceptance of the suggestion of the Dymek group that the FeO/MnO ratio is dependent on the original oxide-metal ratio in the source materials provides a link between the howardites and certain mesosiderites (section 7.2.6).

A comparison of compositional data on the few olivines present (in Malvern and Molteno only) with published data on the olivines of diogenites suggests that howarditic olivines were not derived exclusively from diogenites. This observation emphasizes the formational complexity of howardites and conforms to the suggestion of DESNOYERS (1982) that howarditic olivines originated from pallasitic, diogenitic, and mesosideritic sources.

The present study of metals in the howardites indicates that metal of primary origin is rare, occurring mainly as inclusions in pyroxenes and in lithic clasts. The majority of metal grains are situated in the glassy microbreccias, with a lesser number in the 'matrix' materials, which they appear to intrude. The Ni and Co contents of these metals show them to be of secondary origin, for they plot in the upper part of the zone of 'meteoritic' metal (GOLDSTEIN and YAKOWITZ, 1971) defined by the compositions of

metals in iron meteorites, pallasites, and chondrites. Both petrographic and chemical studies therefore point to the conclusion that most of the metal grains in howardites are remnants of high-velocity metal-bearing projectiles that impacted on the regolith of the parent body, causing local fusion of the fragmental materials and widespread shock effects of low intensity (section 7.3.3). The observed compositional variation of metals enclosed in glassy microbreccias in Malvern confirms the conclusion of DESNOYERS and JÉROME (1977) that cooling of the glass was too rapid for re-equilibration to take place.

Interpretation of the analytical data on the glassy phases present in the four howardites investigated revealed that, in each meteorite, their compositions show systematic variations that 'mimic', in whole or in part, the trends defined by the bulk compositions of the basaltic achondrites (Chap. 5). The glasses are therefore not the close approximations to the bulk compositions of the host meteorites that would have resulted from complete fusion of the regolith. The glassy materials in Malvern show the closest approach to complete fusion in the four howardites studied. The reason for this is not apparent, but may be related to composition (Malvern is the least magnesian of the four howardites) or to differences in physical properties, cf. the greatly different cooling rates required to produce glasses with the compositions of Bununu and Malvern (section 3.5.2). Most of the glassy materials in the howardites show enrichment, in varying degrees, in Ca and Al relative to the composition of the host meteorite. From this it is concluded that they were formed by fusion of regolithic material similar in aggregate composition to the host but with preferential melting of plagioclase relative to pyroxene; removal of Mg from the melt by quench crystallization of Mg-rich orthopyroxene microlites may have enhanced the Ca-Al enrichment effect (section 7.4.13). This formational process

implies the addition of a minor proportion of exotic glasses to account for compositions more magnesian than the bulk composition of the host. The absence of glassy materials as magnesian as the most Mg-rich howardites may indicate that exotically-formed glasses also were modified by preferential assimilation of plagioclase at their point of origin. The proportion of exotic glass is probably higher in Malvern than in the other howardites studied.

Almost one-third of all the glassy bodies analyzed in the present study proved to contain anomalously high concentrations of K relative to the host howardites. Almost all are 'true' glasses, and almost all occur in Malvern. This distribution coincides with that of glassy phases whose morphology suggests they may have been added to the regolith from external sources. It was therefore concluded that, in the absence of satisfactory mechanisms to explain the enhanced content of K in these glasses, they were formed from source materials with Na/K ratios different from those of the rocks from which the achondrites were derived. A correlation may exist between glasses whose morphologies indicate transport from their places of origin and those with anomalous concentrations of K, but this could not be conclusively established.

9.2.4 A model for the formation of the howardites

Combination of the conclusions presented in the preceding sections enables a model for the formation of the howardites to be devised, taking cognizance of the deduced processes of formation of lunar breccias. Formation of the howardites is the final stage in the genetic model set out in the last part of this chapter, but is only briefly referred to there.

It is envisaged that the achondrite parent body had a concentrically layered structure and that achondritic meteorites were derived from the outer-

most parts of the body, where a possibly discontinuous shell of crustal rocks had developed as a result of igneous processes in the outer mantle that are discussed below. A wide compositional spectrum of rocks had been generated by processes of partial melting and differentiation at or near the surface of the parent body. These rocks, which constituted the source materials for the howardites, formed two distinct compositional series. The first of these, the eucrite series, was composed of pyroxene-plagioclase rocks occurring as rapidly-cooled extrusive flows and shallow intrusives and forming a capping to the other, more magnesian, series whose members crystallized more slowly at greater depths in the crust. This second series consisted of pyroxene-plagioclase rocks compositionally distinct from the eucrites and of a range of pyroxenitic residues from the partial melting processes that had generated the plagioclase-bearing rocks of both series. The heterogeneous crustal shell formed of the rocks of these two series underwent intense bombardment by metal-bearing meteorites that impacted with sufficiently high kinetic energy to excavate even the deeper crustal rocks. Further impacts comminuted and mixed the excavated materials to form a regolith on the surface of the parent body, which is generally assumed to have been an asteroid or similar object of sub-planetary dimensions. Modelling of asteroidal surface dynamics (HOUSEN, 1976) has shown that even very small asteroids (diameter 1 km) are capable of sustaining a regolith, while thicknesses of debris of tens or hundreds of metres may accumulate on larger bodies. The low gravity of bodies of asteroidal dimensions favoured both the build-up of such thick deposits and the distribution of ejecta from cratering impacts on a global scale (HOUSEN et al., 1978).

Continued meteorite bombardment of the parent body regolith and underlying rocks further thickened the deposit and locally fused its constituents. Rapid burial of the impact glasses thus formed prevented the

development of extensive bodies of glassy microbreccia similar to those produced in the relatively unprotected lunar regolith and, by shortening the exposure of the components of the regolith to space, reduced the incidence of features common in the lunar breccias - micro-cratering, solar flare tracks, and high contents of solar gases (HOUSEN et al., 1978). The petrographic evidence points to the majority of the glassy microbreccias having been formed in situ in the regolith. The morphology of the 'true' glasses suggests that at least some of them were transported from impact sites distant from the location in the regolith at which the host howardite was formed. The source materials from which these transported glasses were generated may have been similar to those of the host meteorite, e.g. Bununu and Frankfort, or slightly different in alkali content, e.g. Malvern and Molteno. Evidence of the nature of the projectiles that produced the regolith and partially fused it is preserved in the form of metal inclusions in the glassy bodies and the comminuted 'matrix' material, and in the high concentrations of siderophile elements in the howardites (CHOU et al., 1976). Chou and his co-authors assumed the projectiles to have been chondritic on the basis of the greater abundance of chondrites over differentiated, siderophile-enriched iron or stony-iron meteorites (p. 3503).

A further consequence of the rapid accumulation of the regolith on the achondrite parent body postulated above was that the deposit did not become homogeneous despite the global distribution of ejecta from cratering events. Such inhomogeneity can account for the compositional diversity exhibited by the howardites. In the absence of complete mixing of the constituents of the regolith, sampling bias was locally preserved when lithification of the deposit took place. Thus, in a locality in which material excavated by impact from the more magnesian crustal rocks predominated, magnesian howardites such as Frankfort and Bununu were formed; a higher

proportion of eucritic material in the regolith resulted in howardites such as Malvern and Molteno. Most, if not all, of the materials incorporated in these howardites were, however, related to one another by igneous processes and originated from a common source region (see below). This resulted in the coherent inter-element relationships displayed by the bulk meteorites and also by their constituent phases.

Texturally, the howardites represent immature regolith breccias. This observation is consistent with rapid accumulation, during which the constituents of the regolith were not exposed to meteorite bombardment long enough for them to have been reduced to an equilibrium grain size as happened in the lunar regolith. The equilibrium grain size of about 60 microns determined for Apollo 14 soils (McKAY et al., 1972) is finer than the great majority of clasts in the howardites investigated.

The method proposed above for the production of howarditic breccias that are compositionally distinct from one another though composed of co-genetic materials does not preclude the formation of eucritic and diogenitic meteorites. These were probably excavated from their parent lithological units and ejected into space as unbrecciated fragments or as monomict breccias without having undergone the breakdown, dispersal, and intermixing consequent on prolonged residence in a regolith. Moreover, depending on the interaction of sampling and mixing processes, a binary mixture of eucritic and diogenitic material was not an impossibility and in fact exists in the form of the meteorite Aïoun el Atrouss (LOMENA et al., 1976; DUKE, 1978).

Lithification of the regolith from which the howardites were derived is presumed to have been brought about by sintering in a stress-free environment in a manner similar to that proposed for the Apollo 14 breccias (SIMONDS, 1973). The 'detrital' nature of the howarditic breccias, the abundance of matrix glass, and the absence of recrystallization all suggest

that the howardites correspond to a very low grade (0 or 1) in the scale of metamorphism established for the Apollo 14 breccias by WARNER (1972) and modified and related to temperature by WILLIAMS (1972). The criteria set out by the latter author in his Fig. 1 can be used to estimate the temperature range in which the lithification of the howarditic breccias took place from the petrographic characteristics of the various types of glassy bodies present, viz. the degree of devitrification they exhibit. In the preceding discussion, a distinction was drawn between two main categories of glassy materials. The first comprises the glassy microbreccias and those of the 'true' glasses that were similarly formed in situ and that intrude the surrounding regolith (i.e. the 'matrix'). The second includes those glassy bodies whose rounded outlines, conchoidal fractures, and fluidal characteristics indicate that they were spattered into the regolith as droplets produced by impacts occurring at some indeterminate distance. Members of the first category generally show some degree of devitrification, whereas the more fluid, transported varieties do not. HEWINS and KLEIN (1978) considered that devitrification of the intrusive glasses began with their formation and continued as they cooled rapidly to the glass transition temperature (730°C), and that the other glasses had cooled too quickly for devitrification to occur. The glassy droplets were therefore added to the unconsolidated breccia without devitrification having taken place and, according to the chronological evidence (RAJAN et al., 1975: see discussion below), late in the formational history of the regolith. Subsequent to their incorporation, they were not subjected to temperatures sufficiently high to cause devitrification. This constrains the temperature range within which lithification of howarditic breccias took place to between 650°C (the lower limit of the lithification process) and about 800°C , above which devitrification of the glassy droplets would have occurred (WILLIAMS, 1972). These limits may not,

however, be exact because of compositional differences between lunar and howarditic breccias.

After lithification of the regolith, only slight movements took place, as evidenced by the minor fracturing observed in the petrographic examination. The final event in the formational history of the howardites was the impact that excavated them from the lithified ejecta blanket. This impact had at least enough energy to accelerate some of the excavated fragments to a velocity that enabled them to escape the gravitational pull of the parent body; at most, it may have caused the disruption of the entire body.

9.2.5 Chronology of the events in the formation of the howardites

There is a scarcity of chronological data on the howardites. That the availability of additional data would clarify their assembly history and the understanding of the complex cooling histories of their glassy components was clearly recognized by KLEIN and HEWINS (1979), who advocated the determination both of individual ages for glasses within the same sample and of exposure ages. In the absence of such comprehensive data, the chronology of howardite formation is summarized here, using whatever sources are available.

The published information suggests that individual howardites did not have identical formational histories, but points to a common starting age of about 4.5×10^9 years. This has been established, by ^{40}Ar - ^{39}Ar and ^{87}Rb - ^{87}Sr methods, as the time of crystallization and cooling of lithic components in Kapoeta (DYMEK et al., 1976; RAJAN et al., 1979). Plagioclase crystallization in Bununu and Malvern was estimated (Ar-Ar method) to have taken place at $4.42 \pm 0.04 \times 10^9$ and $4.29 \pm 0.04 \times 10^9$ years respectively, but the Malvern plagioclase is regarded as having been partially reset by the impacts that generated the glass (RAJAN et al., 1975). The consensus of

those who studied Kapoeta was that magmatic activity was relatively short-lived (about 0.2×10^9 years). Bombardment of the parent body surface presumably started in earliest times, and was responsible for the production of glassy material in different parts of the regolith at different periods. Glass in Bununu was formed at $4.24 \pm 0.05 \times 10^9$ years (RAJAN et al., 1975), the time of lunar highland bombardment. Glass in Malvern, however, was formed much later, at about 3.6×10^9 years (RAJAN et al., 1975; KIRSTEN and HORN, 1977), showing that impacts had continued at least till that time. Even later evidence of bombarding projectiles was found in lithic plagioclase in Kapoeta, the age of which was determined as $3.48 \pm 0.04 \times 10^9$ years (RAJAN et al., 1979). There is as yet no evidence whether intense bombardment of the parent body surface continued beyond this time, but the cosmic ray exposure age of Kapoeta is only 3×10^6 years. This establishes the minimum period since it was ejected from the parent body, and presumably indicates that some degree of bombardment of the howardite parent body continued into relatively recent times.

9.2.6 The formation of Binda

Binda displays none of the salient physical characteristics of the howardites and had a different mode of formation. The petrographic investigation (Chap. 3) showed it to be a breccia of essentially monomict character, though the minor content of glassy material appears to complicate this conclusion. Microprobe analyses proved, however, that the compositions of these glassy microbreccias are sufficiently similar to that of the bulk meteorite to establish a genetic connection and to dispel any suggestion of a completely exotic source (sections 7.4.12 and 7.4.13). The textural evidence indicates that Binda was derived from a cumulate of plagioclase and magnesian pyroxene that was shattered in situ by meteorite impact without having been

totally disrupted. Cataclastic effects are much in evidence, but mixing of fragmented material was limited.

That the parental cumulates cooled slowly, possibly in a plutonic environment, is indicated by the well-developed exsolution of a calcic phase in the pyroxenes and the general absence of zonation in both major constituents. This cooling regime apparently did not, however, result in constancy of composition in these constituents. Substantial variations were observed in both plagioclases (section 7.2.1) and pyroxenes (section 7.2.2) that could not be accounted for by analytical imprecision. Moreover, these variations are not random, but conform to recognized differentiation trends and are present in all the inter-element relationships studied; for instance, a coherent relationship is well displayed even by the minor elements Al, Ti, and Cr in the Binda pyroxenes (Fig. 7.20). Such systematic variability must be ascribed to the original crystallization of the parental cumulate. Equilibration during slow cooling evidently did not eliminate original compositional differences in the constituent pyroxenes and plagioclases.

The presence of compositional variability in the Binda source rocks at the time of the impacts that produced the brecciation and formed the glassy materials may, in conjunction with selective fusion of plagioclase, explain the variations observed in these materials. The variation trends in the Binda glassy microbreccias do not in general coincide with those established for the bulk achondrites, although they are similar, and appear to have been affected by plagioclase incorporation to a greater degree than the howarditic glassy materials. In some inter-element relationships, particularly those involving Fe, the Binda glassy materials have closer affinities with the bulk compositions of the mesosideritic silicates than with the achondrites (see section 7.4). This observation is in agreement with the proposition advanced in this work that Binda originated from mesosideritic

source rocks. The main evidence in support of this is reviewed in a later section of this chapter.

No indications were found that Binda had undergone metamorphism other than cataclastic action and lithification. If it is indeed mesosideritic, its petrographic characteristics place it in sub-group 1 (POWELL, 1971, Table 4) along with the mesosiderites that it most closely resembles compositionally - Barea, Dyarrl Island, Patwar, and Vaca Muerta (FLORAN, 1978).

There is no evidence that Binda ever formed part of a regolith. It is envisaged that the source rocks from which it was derived crystallized and accumulated at some depth below the surface of the parent body, and that Binda was excavated and ejected into space by a major impact. Such an impact may also have caused the brecciation and formed the glassy materials (cf. the proposed formation of monomict and unbrecciated eucrites and diogenites, section 9.2.4).

9.2.7 The chronology of Binda

Unlike breccias formed in a regolith, Binda does not present the potential for dating events in a complex assembly history. Using the ^{87}Rb - ^{87}Sr method, BIRCK and ALLÈGRE (1978b) determined a whole-rock age of 4.6×10^9 years for the meteorite. The same technique was used to establish a mineral age of $3.450 \pm 0.340 \times 10^9$ years, which was interpreted as a re-setting of the Rb-Sr 'clock' by metamorphism or shock (BIRCK and ALLÈGRE, 1979). This may date the brecciation of Binda. The close correspondence with the time of formation of glass in Malvern and similar ages in lithic clasts in Kapoeta is worthy of note, as is the early date of crystallization of the whole rock. The latter point is returned to below.

9.3 GENETIC PROCESSES IN THE FORMATION OF THE ACHONDRITES

9.3.1 Introduction

In this section, conclusions based on the bulk compositional data on 42 achondrites and mesosiderites are reviewed and discussed from the standpoint of the genetic processes that produced the three main classes of achondrites. These processes provided the source materials from which the howardites were formed in surface and near-surface environments (as discussed above), and are thought of as having operated in the upper mantle and deeper crustal regions of the parent body. Corroborative evidence concerning these processes, derived from computer modelling of eucrite genesis (Chap. 8), is also taken into account.

9.3.2 Refractory element enrichment

Study of the inter-element relationships in the refractory elements (including trace elements) in achondrites and the silicate portions of mesosiderites showed different trends of enrichment in different meteorite classes. A basic sub-division can be made in the achondrites into a eucrite series and a series consisting of the more magnesian achondrites - howardites and diogenites. In previous studies of refractory element behaviour, a trend was recognized in some relationships that was regarded as encompassing all three achondrite classes. The present investigation shows, however, that the enrichment trend in the eucrites is generally significantly different and quite distinct from that of the howardites and diogenites, but that both trends suggest an origin from the operation of processes of igneous differentiation. Independent confirmation of these enrichment trends is to be found in a study of trace elements (e.g. Sc, a refractory element not included in the current study) in achondritic pyroxenes (GÖPEL and WÄNKE, 1978). Mg-rich cumulates contain the lowest concentrations of refractories in both

trends while in the eucrites the greatest enrichments in these elements are present either in late-stage differentiates from primary melts, e.g. Nuevo Laredo, or in liquids produced by very small amounts of partial melting, e.g. Stannern (section 5.2). The two-fold division of the achondrites is in accord with the genetic hypothesis of STOLPER (1977a) that is used, in a modified form, in the model for the formation of the achondrites presented in the last section of this chapter.

This study provides new information on refractory element behaviour in the silicates of the mesosiderites and demonstrates their lack of identity with the howardites, a conclusion supported by the detailed modal studies of PRINZ et al. (1980). Their enrichment trends coincide with those of the howardites in only a few relationships (e.g. Ti/Ba; Fig. 5.8) in which all achondrites define a single trend, but even in these special relationships the mesosiderites plot with more scatter than the achondrites. In general, inter-element plots reveal clear enrichment trends that suggest an evolutionary sequence in the mesosiderites. In some refractory relationships, however, the coherence is poorer, e.g. Sr/Ba (Fig. 5.9). The mesosiderites, unlike the achondrites, have been metamorphosed in varying degrees (POWELL, 1971; FLORAN, 1978). Re-distribution of elements, particularly trace elements, during metamorphism may account for the less coherent inter-element relationships displayed by the mesosiderites. There is, however, no clear correlation between metamorphic grade and enrichment in the refractory elements; Emery and Łowicz, highly metamorphosed members of sub-group 3 (POWELL, 1971), consistently show the greatest degree of enrichment, whereas Mincy - another member of the same group - equally consistently shows the least.

In the study of refractory element behaviour, and in other parts of the present investigation involving trace element concentrations,

inadequacies in the available data became apparent. In some instances these occur in meteorites critical to the solution of the problem, e.g. in the determination of the position or extension of an evolutionary trend. Invariably the most coherent results came from studies (in this laboratory or elsewhere) in which major, minor, and trace element concentrations had been determined on the same samples. The problem is compounded by the lack, complete or partial, of published trace element data for many meteorites. For these reasons an important group of refractory elements - the rare earth elements - is not included in the present study. Their determination is not possible in this laboratory, but an attempt was made to overcome this deficiency by embarking on a co-operative project with a European university. Aliquots from samples of achondrites analyzed in this laboratory (Haraiya, Macibini, Molteno, Kapoeta, Chaves, Frankfort (T), Binda, Shalka, and Tatahouine; this work, and McCARTHY, 1971) were dispatched for analysis by neutron activation. Mesosideritic silicates were not included because insufficient material remained after analysis. Unfortunately, no results have yet been communicated to the writer. It is, however, important that reliable REE data should be obtained on a range of achondritic and mesosideritic samples for use in testing the hypotheses presented in this work.

9.3.3 Mathematical modelling of the genesis of the eucrite series

The trends evident in plotted inter-element relationships (involving non-refractory as well as refractory elements) indicate that most of the eucrites constitute a series of related rocks that is distinct from the howardites and diogenites except that, in general, a trend defined by these latter two classes, if extended, passes through the greatest concentration of eucrites on the corresponding eucrite trend. These are the eucrites regarded by STOLPER (1977a) as 'primary', i.e. formed by low degrees of

partial melting of the source material, or by small amounts of fractional crystallization from these partial melts. The remaining eucrites on the trend have the characteristics of cumulates or residual liquids, but STOLPER (1977a) contended that only the liquids were derived from the 'primary' melts. Mathematical modelling was used (Chap. 8) to test the validity of this view, which is at variance with the simpler explanation for the origin of the cumulate eucrites suggested by the coherency of the inter-element relationships described in Chap. 5. This approach showed that a residual liquid similar to Nuevo Laredo could be produced from an initial liquid with the composition of Sioux County - one of the 'primary' melts - by subtraction of an assemblage consisting of pigeonite, plagioclase, chromite, and metallic Fe and representing 32% solidification of the initial melt, a figure in good agreement with similar calculations by STOLPER (1977a), CONSOLMAGNO and DRAKE (1977), and REID et al. (1979). The subtracted assemblage was shown to be modally almost identical to the cumulate eucrite Moama. Similar fractional crystallization modelling of major element compositions led REID et al. (1979) to conclude that Moore County and Serra de Magé are complementary cumulates to the Fe-rich residual eucritic liquids such as Nuevo Laredo. It was concluded, therefore, from the evidence of the present study and related investigations, that the eucrites studied essentially represent a differentiation series that originated from a single-stage process of fractional crystallization of 'primary' partial melts, not from the more complex two-stage process advocated by STOLPER (1977a and b).

Further evidence in support of this conclusion was considered (section 8.4), and centred on Stolper's contention that the pyroxenes of cumulate eucrites could have equilibrated only with liquids more Fe-rich than any known eucrites. The most telling argument against this hypothesis is found in the experimental data of Stolper himself. Melting experiments on

Juvinas and Sioux County produced pyroxenes more magnesian than those of the cumulate eucrites while the corresponding residual liquids attained Fe/Fe+Mg ratios greater than the most Fe-rich eucrites known (Nuevo Laredo and Lakan-gaon). These data show that the cumulate eucrites, and residual liquids sufficiently Fe-rich to have been in equilibrium with the pyroxenes of these cumulates, could have been generated from the 'primary' eucritic melts in a single-stage process involving high degrees of fractional crystallization.

This conclusion assumes the validity of the experimentally-determined distribution coefficient $K_D^{Fe/Mg} = 0.30$ for clinopyroxene-liquid partitioning (STOLPER, 1977a) throughout the generation of the eucrite series. This value is critical to Stolper's objections to the cumulate eucrites having been fractionated directly from 'primary' eucrites such as Juvinas and Sioux County. The possible effects that temperature, changing compositions of residual liquids, and departures from equilibrium attendant on rapid rates of cooling might have had on the value of this distribution coefficient were subjected to speculative discussion (section 8.4). It was tentatively concluded that, under certain circumstances, changes in composition or cooling rate could have brought about increases in the distribution coefficient that would have favoured the formation of cumulate eucrites from 'primary' eucritic melts. In particular, the study suggested that cumulate bodies, probably smaller than those formed under plutonic conditions, could have been produced in near-surface environments in which high cooling rates, accompanied by increased values of $K_D^{Fe/Mg}$ (clinopyroxene-liquid), prevailed.

9.3.4 Derivation of source materials for achondrites from a mesosideritic upper mantle

The parallelism of the trends in the distribution of achondrites and mesosiderites in the Mg-Ca relationship (section 5.3.1) indicates the possible existence of a genetic factor common to both types of meteorite.

This was deduced to be the variable degree to which the original content of metallic Fe in the most primitive mesosiderites had been oxidized. The endpoint of this process of progressive oxidation, which possibly increased in near-surface environments, was envisaged as the production of a crustal zone in the parent body that corresponded to the source material from which the main classes of achondrites were derived. Unoxidized metal may have remained, but may have not played a major role in the genesis of the achondrites (STOLPER, 1977a, p. 596). In support of this hypothesis, it was shown that almost all the mesosiderites studied contain approximately the same amount of total (i.e. metal + sulphide + oxide + silicate) Fe. The only real exception is Dyarri Island, which may be an unrepresentative sample or may have come from a different source region (cf. HEWINS, 1979b, p. 1120).

It was further shown (section 5.3.3) that averaged compositions of various groupings of achondrites and 'oxidized' mesosiderites could be brought into correspondence with the average calculated for the 'primitive' mesosiderites of the main group by the mathematical removal of the 'dilution' effect of FeO. The closest correspondence was obtained from howardites analyzed in the same laboratory by the same analytical technique. This suggests that the average composition of the howardites, which may themselves be regarded as 'averages' of their particular source regions, is a close approximation to the source material of the achondrites, biased only by the exclusion of the most deeply buried (and therefore least frequently excavated) differentiates. The factors required to effect correspondence of the selected howardite group and the 'oxidized' mesosiderites with the 'primitive' mesosiderites were used to recalculate the major element compositions of all the meteorites studied except the five 'primitive' mesosiderites regarded as the initial mantle material. Plotting of the recalculated data in several inter-element relationships showed that coincidence with the trend of the 'primitive'

mesosiderites resulted, and this further supported the hypothesis of progressive oxidation stated above. This conclusion, however, was restricted to major element compositions and could not be demonstrated for trace elements. No reason for this could be suggested other than possible redistribution as a consequence of metamorphism; cf. refractory trace element behaviour (section 9.3.2). It is possible that metamorphism may have affected the more deeply-buried mesosiderites after establishment of the pattern of oxidation that determined the range of bulk compositions suggested by the proposed formational model.

This part of the investigation showed also that the mesosiderites obey Prior's Rules in a general way. The data indicate a rough division into two groups, one of which includes the 'primitive' mesosiderites, the other the more oxidized varieties. The correspondence is not perfect, but shows a fair degree of consistency throughout observable parameters such as Fe/Fe+Mg ratios and concentrations of siderophile elements. A generalized summary of the available information is presented in Fig. 9.1.

9.3.5 Variations in Mg and Cr in achondrites and mesosiderites

A well-developed positive correlation between the concentrations of Mg and Cr in the achondrites studied points to the operation of systematic igneous processes in their formation. The eucrites show little variation in either element but, by contrast, the diogenites exhibit a wide range of Cr concentrations at almost constant Mg; the 'average diogenite' does, however, lie on the achondrite trend. It was concluded that the diogenites are inhomogeneous with regard to the distribution of chromite, layering being a possibility. The mesosideritic silicates display no coherent relationship of Mg and Cr, and no conclusions could therefore be drawn.

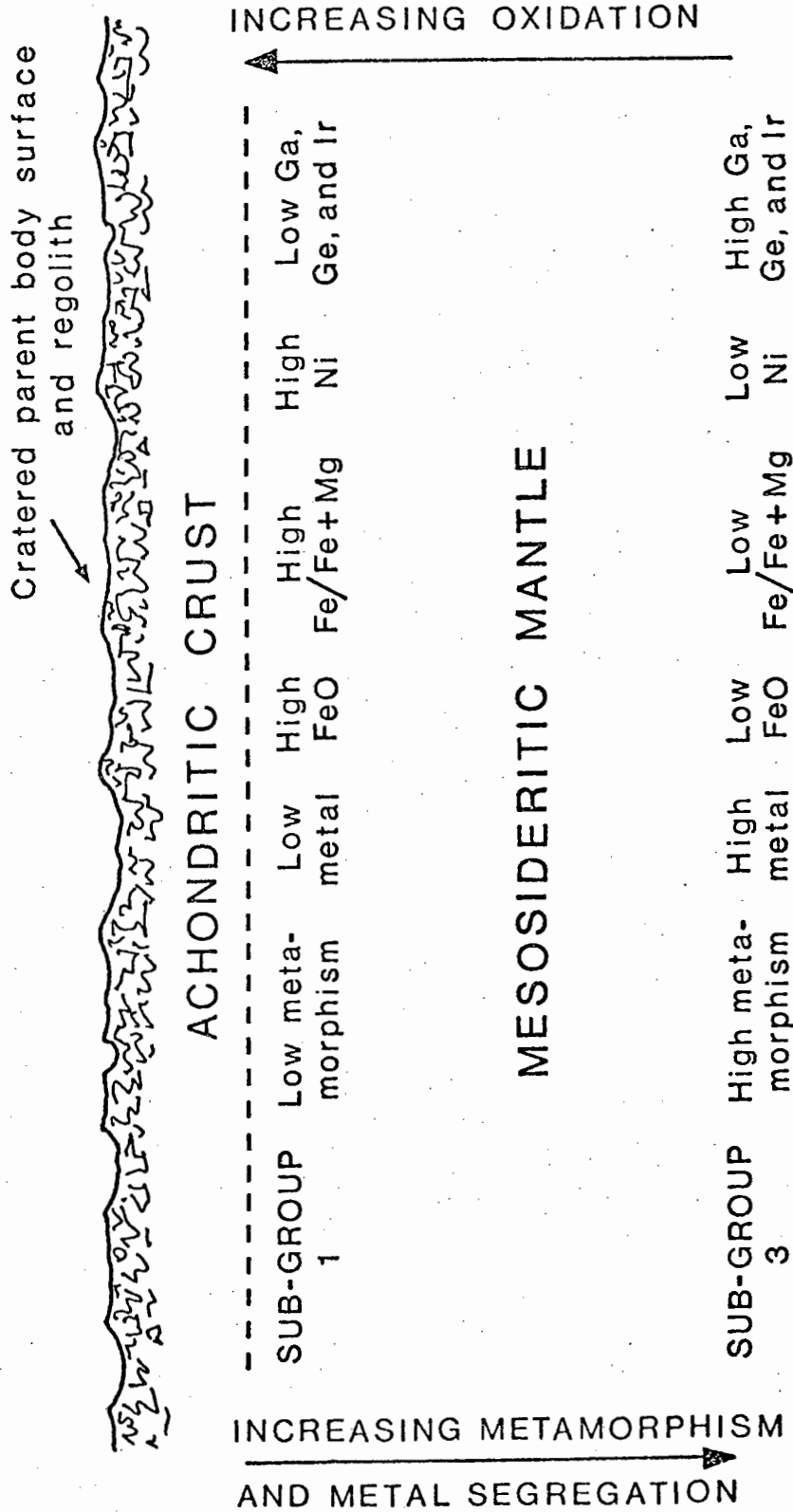


Fig. 9.1. A diagrammatic summary of the variations in the mesosideritic mantle from which it is proposed that achondritic source material was derived by progressive oxidation of metal. 'Sub-groups' refer to the classification of POWELL (1971).

9.3.6 Fractionation of the Ca/Al ratio in achondrites and mesosiderites

STOLPER (1977a) noted that the Ca/Al ratio was fractionated with respect to Ti, both in natural eucrites and in the products of his melting experiments. Extension of Stolper's study to the achondrites and mesosiderites of the present investigation and to other indices of differentiation confirmed his observation (section 5.5). The eucrite series was shown to be a discrete entity with features consistent with an origin by fractionation of pigeonite and plagioclase from the 'primary' eucritic melts. However, the howardites (and possibly the diogenites also) plot on a trend that indicates an evolutionary process different from that of the eucrite series. Decrease in the index of differentiation plotted (concentrations of the incompatible elements Ti or Zr, or the Fe/Fe+Mg ratio) is consistently accompanied by increase in the Ca/Al ratio, albeit slight. This is in accordance with the process envisaged in the model presented below for the production of the materials from which the howardites were derived, viz. progressive partial melting of the residues left in the source region after generation of the eucrite series. Increase in the Ca/Al ratio could have resulted from slight preferential partitioning of Al into the partial melts. Magnesian pyroxenes in howardites that have not crystallized in association with plagioclase (i.e. En content greater than 60) tend to show an increase in Ca/Al ratios with increase in Mg concentration, but this cannot be rigorously demonstrated.

The howardites do not, however, all plot on the trend discussed above, and the possibility of a mixing, rather than an igneous, process was investigated according to the general principles governing such processes in ratio-element plots (LANGMUIR et al., 1978). This is more fully discussed below, but it was concluded that mixing could not be established in relationships involving the Ca/Al ratio.

9.3.7 Fractionation of refractory elements in the meteorites studied

Fractionation of refractory elements during the igneous processes that generated the achondrites and mesosiderites was studied by plotting their concentrations against the $\text{Fe}/\text{Fe}+\text{Mg}$ ratio as an index of differentiation (section 5.6). All the elements plotted are incompatible in processes involving fractionation of pigeonite and plagioclase except Sr. It was found that the eucrite series showed a positive correlation between the concentrations of these elements and the progress of differentiation. A similar relationship exists in the more magnesian achondrites, but these define a trend of different slope. No coherent relationship was observed in the mesosiderite silicates, presumably indicating the operation of different genetic processes or element redistribution by metamorphism.

In this part of the study, however, two factors emerged that complicate understanding of the formation of the magnesian series of achondrites. Firstly, the most magnesian howardite samples conform to the trend only in the plot that involves Ti. This suggests the existence of a subsidiary trend, but confirmation could come only from the diogenites, on which data are totally lacking. Secondly, hyperbolic mixing curves linking diogenites, howardites, and 'primary' eucrites (LANGMUIR *et al.*, 1978) could be calculated in the Ti vs $\text{Fe}/\text{Fe}+\text{Mg}$ relationship (section 5.6.1). No firm conclusions can be based on these observations, but, considered in conjunction with the complications noted in the distribution of the howardites in relationships involving the Ca/Al ratio (section 9.3.6), they suggest that while the howardites may have followed a general pattern of development, small-scale differences in mode of formation may have existed.

9.3.8 Mixing processes in achondrite formation

Certain achondrites - howardites and polymict eucrites - have been formed by mixing in a regolith. The nature of the source rocks that contributed to these mixtures is less evident. The present study has indicated that howardites are mixtures containing eucritic and diogenitic materials, but are not mixtures of eucrites and diogenites. All lines of evidence point to their formation from a variety of source materials - members of the eucrite series, diogenite-like residues from the partial melting sequences that produced the 'primary' eucrites, and a possibly discontinuous series of partial melts generated from these residues. Such a process, which would account for the continuity of the compositional ranges observed in howarditic pyroxenes and plagioclases, the serial variation in the bulk compositions of howardites, and the alignment of these compositions in a trend that follows the pyroxene-olivine phase boundary in the silica-olivine-anorthite 'pseudo-liquidus' projection (STOLPER, 1977a; Fig. 5.32 of this work), is further discussed in the final part of this chapter.

The mixing that produced the howardites appears therefore to have been partly determined by the igneous processes following the formation of the eucrites as a differentiated series. It is proposed that the source materials for the polymict eucrites were formed in the early stages of these processes of partial fusion of the materials remaining in the source area after generation of the 'primary' eucritic melts. These residues were magnesian but contained trapped feldspathic melt without which further melting would not have taken place (STOLPER, 1977a, p. 600). Fragmentation and mixing in an area dominated by these early second-stage partial melts would explain the position of Macibini on the pyroxene-olivine boundary between the 'primary' eucrites and the most Fe-rich howardites in Fig. 5.32. Support for this proposal may be found in the proximity to Macibini of the plotted

position of Allan Hills 7605 in some of the inter-element relationships studied. This Antarctic meteorite is the only other polymict eucrite for which suitable bulk compositional data are available. Additional data are obviously required but, for instance, Allan Hills 7605 appears to be associated, along with Macibini, with the enrichment trend for the magnesian achondrite series in Fig. 5.23, not with that of the eucrite series.

9.3.9 Possible source region compositions and the residues from partial melting

In some of the plotted relationships examined in Chap. 5, it was possible to test the applicability of compositions suggested for the source materials for the achondrites by STOLPER (1977a) to the range of meteorites included in the present investigation. Stolper provided only modal estimates for two possible source regions, but bulk compositions were calculated from compositional data on the mineral phases crystallized during his experiments (section 5.5.1). Plotting of these calculated data in various inter-element relationships consistently showed that Source Region 2, estimated to contain 5% plagioclase, 90% pyroxene, 5% spinel, and negligible olivine, was more closely associated than Source Region 1 with the evolutionary trends of the achondrites. No conclusion could have been drawn from this observation alone, but confirmatory indications resulted from a study of the nature of the residues that would have been produced in each of the source regions by the various degrees of partial melting regarded as necessary for the generation of the eucrites Juvinas, Sioux County, Stannern, and Haraiya. The compositional field occupied by the residues from partial melting of Source Region 2 consistently plots on the achondrite trend, between the most magnesian howardites and the diogenites, particularly the diogenite Ellement. By contrast, the corresponding field for Source Region 1 falls outside the limits of the plot in every relationship except that between the Ca/Al and

Fe/Fe+Mg ratios (Fig. 5.22), and even in that instance it appears devoid of genetic significance.

The correspondence between the compositions estimated for Source Region 2 and its associated residues on the one hand, and hypothetical evolutionary trends for the achondrites based on experimental and analytical data on the other, point to the validity of considering the source material from which the achondrites were derived as consisting of 5% plagioclase (An_{94}), 90% pyroxene (Wo_5En_{65}), and 5% Cr-rich spinel. If metal were present in the assemblage, it played little part in the formation of the achondrites, as discussed above. There is consistency with petrographic observations in the proposition that the residues are diogenites and Fe-rich diogenites. The bulk composition calculated for Source Region 2 also corresponds closely to an estimate of that of the primary material of the eucrite parent body (PR*; DREIBUS et al., 1977) and to that of the howardite Yamato 7308, considered by PALME et al. (1978) as chemically very similar to the material from which eucrites and diogenites were formed (section 5.10.2). Comparison with other estimates is made in the final part of this chapter.

9.3.10 Trends in major element concentrations

Variations in the five principal major elements - Si, Al, Fe, Mg, and Ca - were studied in a series of ternary plots (section 5.9). These plots confirmed the continuous trends established in binary relationships, and also clearly distinguished between the eucrite series and those achondrites formed by increasing amounts of partial melting of the material residual from eucrite formation. The trends established showed also the close similarity that exists between howardites and mesosideritic silicates in ternary relationships not involving Fe. This is interpreted as lending support to the hypothesis, summarized in section 9.3.4, of derivation of

achondritic source material by progressive oxidation of the metal of 'primitive' mesosiderites.

9.3.11 Problems in classification in relation to proposed genetic processes

Attention was given in this study to the problematical classification of Binda - variously regarded as a howardite, a eucrite, or a cumulate eucrite, the last being the most recent 'classification' - and of Macibini which, although classed as a eucrite, appears to possess the characteristics of a howardite rich in Fe. It was demonstrated beyond reasonable doubt in all the inter-element relationships studied that Binda bears little compositional resemblance either to the cumulate eucrites or to any other members of the eucrite series. In some plots, Binda falls on the achondrite trend in the vicinity of the more magnesian howardites but, in view of its more general location off the trend, this is regarded as coincidental and without genetic significance. The meteorite does, however, plot in close association with the mesosideritic silicates, whether they define a trend or merely an irregular field in the relationships plotted. It was therefore concluded, albeit tentatively, that Binda may represent a cumulate 'clot' that originated from mesosideritic rocks, possibly of a fairly highly oxidized variety in order to account for the compositional similarities to howardites (section 5.7).

Independent support for the writer's view that Binda is not a cumulate eucrite may be found in the modelling of eucrite genesis carried out by REID et al. (1979). These authors found that Binda could not be successfully derived from 'primary' eucritic melts by fractional crystallization of pyroxene and plagioclase of the compositions present in the meteorite, whereas no such difficulty was encountered with the cumulate eucrites Moore County and Serra de Magé.

SIMPSON and AHRENS (1979) suggested that Macibini might advantage-

ously be re-classified as a howardite on the basis of its polymict character and its association with the howardites in certain inter-element plots, e.g. Ti versus Fe/Fe+Mg. The present study has shown that in many inter-element relationships, Macibini occupies a plotted position intermediate between Malvern and the 'primary' eucrites, either on the trend of the magnesian achondrites or on its extension. With the increased availability of data on the Antarctic polymict eucrites, it appears possible (as suggested in section 9.3.8) that these meteorites may have been produced in the early stages of the sequence of partial melting events that provided the range of magnesian materials present in howardites, i.e. subsequent to the formation of the main eucritic differentiation series. If this hypothetical suggestion could be proved true, there would then be less genetic basis for a distinction between howardites and polymict eucrites. More bulk compositional data on the polymict eucrites are required to clarify their relationship to other achondrites.

A further classificatory change may become desirable if sufficient support becomes available from new sources, e.g. the Antarctic meteorite finds. The term 'diogenite' may have to be broadened to include a range of pyroxenitic rocks that may have originated as residues partly from the formation of the eucrite series and partly from the second stage of partial melting that produced the melts, compositionally intermediate to eucrites and diogenites, for whose existence the howardites provide evidence. The model for achondrite formation presented below proposes the generation of such a range of pyroxenitic residues, and this proposal is supported by the presence in howardites of a continuum of orthopyroxene compositions that includes the very restricted range exhibited by diogenites sensu stricto (En₇₂-En₇₄; FLORAN et al., 1977; see section 7.2.3 for the full compositional spectrum of howarditic pyroxenes). Further support may be found in the

discovery in the Antarctic of an Fe-rich diogenite, Yamato 75032, in which the pyroxenes have compositions of about En_{65} (TAKEDA et al., 1979). The present writer does not subscribe fully to the view expressed by Takeda and his colleagues that this diogenite represents a close genetic link between diogenites and eucrites. There may, however, be a link between Yamato 75032 and the polymict eucrite Yamato 74450, as they suggest (p. 89).

9.4 A MODEL FOR THE FORMATION OF THE ACHONDRITES

9.4.1 Introduction

In this, the final part of this report, a model is presented for the formation of the three main classes of achondrites that attempts to relate the information gathered in the investigation to current thinking on this topic. A brief comparison with other models is included. The present work has drawn throughout on the ideas expressed by STOLPER (1977a) and has used these concepts as a starting point to which the current data have been added. In general, the result has been confirmation of the Stolper model, but modifications have been suggested where appropriate, e.g. in the formation of the cumulate eucrites. The picture that has emerged requires confirmation in aspects in which vital data are at present either inadequate or totally lacking, and it is to be hoped that this work will stimulate further investigations that will fill the gaps in our knowledge.

9.4.2 The model

It is implicit in the model presented here that the three main classes of achondrites were formed in the same parent body, and that the mesosiderites also formed part of that body (cf. DESNOYERS, 1982). If more than one parent body was involved, then these essential constraints applied to all. A different view, viz. that achondrites and mesosiderites originated

in separate bodies, has been expressed (MITTLEFEHLDT, 1977, 1978; MITTLEFEHLDT et al., 1979) but has been less firmly stated in more recent papers (MITTLEFEHLDT, 1979a, 1979b). Current thinking favours an asteroid as the achondrite parent body, with 4 Vesta as the most likely choice (McCORD et al., 1970; LARSON and FINK, 1975; CHAPMAN, 1976; and CONSOLMAGNO and DRAKE, 1977). The features of this particular asteroid that, related to the present study, support its candidature are as follows: (1) Spectral reflectance studies have shown that its surface composition approximates that of the basaltic achondrites (McCORD et al., 1970); additional data indicate that the surface consists of Fe-rich pigeonite and plagioclase, and is devoid of olivine (LARSON and FINK, 1975). (2) It is large enough (diameter 500 km) to have undergone heating sufficient to cause melting and differentiation, i.e. heat produced was not radiated so fast that melting temperatures were not attained, as in smaller bodies (CHAPMAN, 1976). (3) Its size allowed eruption of eucritic melts to form a crust that protected the underlying differentiated mantle (CONSOLMAGNO and DRAKE, 1977). (4) Vesta is nearly spherical; variations in its albedo with rotation therefore truly indicate slight departures from uniformity of its surface composition (DEGEWIJ et al., 1979), as suggested by the model presented here.

Further support for an asteroidal parent body was provided by ANDERS (1978) who, reasoning from contents of solar-wind gases and cratering rates in relation to the lunar situation, demonstrated that 'gas-rich' meteorites originated from the main belt asteroids. Moreover, the high proportion of 'gas-rich' meteorites (e.g. 33% of all howardites) indicates their origin in a body large enough to sustain the "substantial regolith" that would be generated by prolonged residence in the asteroid belt.

Objections to the asteroids in general as sources of meteorites are of an astronomical nature, based on the dynamic difficulty of getting

material from parts of the asteroid belt into Earth-crossing orbits (see, for instance, WETHERILL, 1976). These objections apply particularly to Vesta, which is unfavourably situated. However, a mechanism was proposed by HOSTETLER and DRAKE (1978) which, if proved dynamically valid, would indicate a greatly enhanced probability of achondritic material ejected from Vesta arriving on Earth.

Further information on the nature of the achondrite parent body comes from oxygen isotope studies employing three-isotope plots ($^{17}\text{O}/^{16}\text{O}$ versus $^{18}\text{O}/^{16}\text{O}$) for a variety of terrestrial and extra-terrestrial materials. These plots define groups that presumably originated in different parts of an inhomogeneous solar nebula and that could not be derived from one another by simple mass-fractionation (CLAYTON and MAYEDA, 1975; CLAYTON et al., 1976). The 'terrestrial group' includes the Earth, the Moon, the differentiated meteorites, and the enstatite chondrites, whereas the H chondrites, the L chondrites, and the various components of carbonaceous chondrites all fall on individual fractionation trends or on mixing lines produced by the incorporation of variable amounts of a possibly pre-solar constituent very highly enriched in ^{16}O (CLAYTON et al., 1973). The significance of these conclusions to the present model is that the data are consistent with derivation of the mesosiderites and pallasites from the same ultimate source material as the eucrites, howardites, and diogenites, and possibly from the same parent body (CLAYTON and MAYEDA, 1978a), and that the oxygen isotope studies produced no evidence to suggest that chondrites and achondrites could have come from a common parent body (CLAYTON and MAYEDA, 1978b). The body in which these differentiated meteorites originated may, apart from depletion in volatiles, have had chondritic element abundances, as claimed by some workers (e.g. CONSOLMAGNO and DRAKE, 1977), but was not formed from unmodified chondritic material (CLAYTON et al., 1976). These studies do not, however, invalidate

the conclusion of TAYLOR and EPSTEIN (1970) that basaltic achondrites did not come from the Moon (see Chap. 2); differences in ^{18}O militate against that possibility (CLAYTON and MAYEDA, 1975).

The oxygen isotope data are consistent also with extensive melting and differentiation of the achondrite parent body, possibly by short-lived energy sources (CLAYTON and MAYEDA, 1975; CLAYTON et al., 1976). It is generally held (e.g. CHAPMAN, 1976) that heating, differentiation, and cooling of the parent body took place within about 200 million years of the formation of the solar system about 4.6×10^9 years ago. BIRCK and ALLÈGRE (1978a) determined "the best differentiation age for eucrites" as $4.57 \pm 0.13 \times 10^9$ years from ^{87}Rb - ^{87}Sr measurements. The ages of individual eucrites confirm this conclusion; MANHES and ALLÈGRE (1978) used lead-lead dating to establish the age of Juvinas as $4.549 \pm 0.003 \times 10^9$ years, while TATSUMOTO et al. (1973) used the same technique to determine slightly younger ages for Sioux County and Nuevo Laredo (4.526×10^9 and 4.529×10^9 years respectively). Sm-Nd methods gave the age of Juvinas as $4.56 \pm 0.08 \times 10^9$ years (LUGMAIR et al., 1976) and that of Pasamonte as $4.58 \pm 0.12 \times 10^9$ years (UNRUH et al., 1977).

A recent study of diogenites (BIRCK and ALLÈGRE, 1981) yielded an Rb-Sr age of $4.45 \pm 0.18 \times 10^9$ years for the class, considered as a discrete entity as required by the two-stage genetic model presented here; Birck and Allègre went on to derive a single isochron for diogenites and eucrites, a step that, in the opinion of the present writer, may obscure a significant time difference in the formation of these meteorite classes. It is important also for the model under discussion to bear in mind the very early age (4.6×10^9 years) determined for Binda by BIRCK and ALLÈGRE (1978b). This age pre-dates formation of the 'primary' eucritic melts, as might be expected from the present model, whereas the cumulate eucrite Serra de Magé was dated

at $4.41 \pm 0.02 \times 10^9$ years by the Sm-Nd method (LUGMAIR et al., 1977). The same technique gave ages of $4.58 \pm 0.05 \times 10^9$ years for Moama (HAMEY et al., 1978) and $4.60 \pm 0.03 \times 10^9$ years for Moore County (NAKAMURA et al., 1977), indicating a very close relationship to the 'primary' eucrites. Unfortunately, little work has been done on dating the mesosiderites. MURTHY et al. (1977) obtained an Rb-Sr internal isochron age of $4.35 \pm 0.10 \times 10^9$ years for Estherville, but this may date only the recrystallization of the meteorite, which was re-assigned to sub-group 3 by FLORAN (1978).

Possible sources for the intense heating of the achondrite parent body that, although it operated for only a relatively short period immediately following accretion, was effective in differentiating the body were reviewed by MITTLEFEHLDT (1979a). After consideration of an internal heating model, in which the heat sources were either ^{26}Al or electrical induction, he concluded that external heating caused by impacts on the parent body surface was more compatible with the geochemical data. In an externally-heated body, heat energy from large impacts would effectively be 'buried' by the development of a regolith and possibly also by continued accretion to the body. This heating could have produced melting and differentiation in the outermost parts of the body, with the eventual formation of a basaltic crust. The suggested depth to which heating would have been effective is of the order of tens of kilometres for an asteroidal body of 300 km, i.e. considerably smaller than 4 Vesta. The external heating model implies that no core of Fe-Ni metal was formed in the body because the cold interior had sufficient strength to limit the sinking and segregation of such metal.

The concept that emerges from the evidence discussed above is therefore that of a parent body accreted very early in the formation of the solar system and heated by external agencies (meteoroid bombardment and accretional energy) to the point that melting and primary differentiation

took place in at least the outermost parts of the body at an early stage in its formation. A difficulty arises when the nature of the primordial material that accreted to form the body is considered. Most workers are of the view that it was near-chondritic, and produce models of achondrite genesis apparently consistent with the available compositional evidence that are based on this assumption. However, this approach is at variance with one of the conclusions indicated by the oxygen isotope studies of the Clayton group, viz. that members of the 'terrestrial group', which includes all the differentiated meteorites, cannot be derived by direct fractionation from either the ordinary or the carbonaceous chondrites (CLAYTON et al., 1976). To attempt to resolve this paradox is beyond the scope of the present investigation. For the present purpose, i.e. the formulation of a model for the genesis of the achondrites that is in general accord with the data of the study reported here, it must be assumed that the primary differentiation that took place in the parent body was capable of producing a mantle-like zone in which the outer parts at least were compositionally similar to the reduced mesosideritic material typified in this investigation by the five mesosiderites of the 'main' group - Emery, Estherville, Łowicz, Mincy, and Mount Padbury (sections 5.3.2 and 5.3.3). It is tempting to suggest further that the deeper parts of the mantle, or even the complete interior of the parent body if segregation of metal occurred on too limited a scale to permit formation of a Ni-Fe core, were pallasitic in composition, but this must remain speculative. The work of DESNOYERS (1982) does, however, suggest a common parent body for pallasites, mesosiderites, diogenites, howardites, and eucrites.

The proposal, implicit in this model, that mesosiderites originated at depth in a parent body with the dimensions of 4 Vesta, may receive some support from the extremely slow cooling rate of $0.1^{\circ}\text{C}/10^6$ years determined

by POWELL (1969b) for mesosideritic metal. This rate was confirmed for Estherville by CROZAZ (1978) and by KULPECZ and HEWINS (1978) for schreibersite growth in Emery. These are metamorphosed mesosiderites belonging to sub-group 3 (POWELL, 1971; FLORAN, 1978), and here regarded as 'primary'. It is possible, therefore, that the slow cooling rate of such mesosiderites may indicate origin at considerable depth, or metamorphic re-heating, or a combination of both.

As summarized in section 9.3.4, the proposed formational model calls for progressive oxidation of the original metal content of the 'primitive' mesosideritic material present in the upper mantle of the parent body, with the ultimate production of a near-surface zone of material modally and compositionally similar to one of the source regions suggested by STOLPER (1977a); see sections 5.5.1 and 9.3.9, where this composition is referred to as Source Region 2. Energy for the partial melting of this source material, with the production of achondrites according to the scheme - modified from STOLPER (1977a) on the basis of the data of the present study - described below, was derived from external sources either directly, as in the primary differentiation, or indirectly in the form of impact-generated heat 'buried' in the outer parts of the parent body.

The 'primary' eucrites, e.g. Juvinas and Sioux County, were the first to be produced from the source material by small degrees of low pressure partial melting (estimated as 15-20% in the model of STOLPER, 1977a), which would just have exhausted plagioclase from the source. Other members of the eucrite series were formed by limited fractional crystallization of plagioclase and pigeonite from these 'primary' melts. Greater degrees of fractionation of these minerals produced residual liquids similar to Nuevo Laredo and Lakangaon and, as shown by this study and others, corresponding cumulates such as Moama, Moore County, and Serra de Magé. The meteorites

cited do not, however, necessarily represent the compositional limits of the eucrite series; the experimental results of STOLPER (1977a) suggest that more extreme differentiates may exist but have not yet been found.

It is not envisaged that this process of eucrite formation was confined to a single location on the parent body. Suitable source materials were presumably available on a global scale, as was the required heat energy also, because it was supplied externally. Local variability in physico-chemical conditions may have resulted in minor variations in eucrite genesis but, as discussed below, probably played a greater role in the second stage of the formation of the achondrites.

Separation and eruption of the eucritic liquids from the source region in the upper mantle resulted in the eventual build-up of a crustal zone on the parent body. This crust was, of course, subjected to continual meteoroid bombardment in the same way as the underlying rocks had previously been. There may have been a critical degree of partial melting at which eucritic liquids separated from their source regions. STOLPER (1977a, p. 608) suggested, on the basis of his observation that most eucrites were produced from primary melts generated by about 20% partial fusion, that that was the critical value. He further pointed out that this degree of partial melting apparently coincided with exhaustion of plagioclase in the source region, and that lack of separation of melts prior to plagioclase exhaustion suggested that conditions close to perfect equilibrium fusion had prevailed during formation of the eucrites. Constraints on the actual separation of partial melts from the source region similar to the constraints suggested for the eucrites may have operated also in the second stage of achondrite genesis, as discussed below.

Formation of the 'primary' eucritic melts appears likely, therefore, to have exhausted plagioclase from the source materials, but complete

separation of plagioclase-bearing liquids did not necessarily occur if the operative process was equilibrium fusion, or even imperfect fractional fusion (STOLPER, 1977a, p. 600). However, whether or not these liquids were removed from the source region had no effect on the crystalline residues from the partial melting process. In the silica-olivine-anorthite 'pseudo-liquidus' projection (Fig. 5.32), these defined a trend of continuous compositional variation originating in Source Region 2 and directed away from the 'primary' eucritic melts clustered around the peritectic A. It is assumed that Source Region 2 lies on the olivine-pyroxene phase boundary (section 5.10.2) thereby causing the trend of residual variation to coincide with this boundary, but this is not critical to the argument since, by definition, olivine is negligible. In theory, the trend of residual composition reached the edge of the pseudo-ternary diagram simultaneously with exhaustion of plagioclase from the source region. This, and other stages of the process proposed for the formation of the achondrites, are schematically illustrated in Fig. 9.2; pyroxene variations associated with these stages are presented in a simplified form in Fig. 9.3.

At this point, two possibilities present themselves; both may have occurred, but in different parts of the source region or of the parent body. The first involves the complete separation of all plagioclase-bearing liquids from the source region (by eruption or intrusion into higher levels of the crust) and therefore from further reaction with the residual materials. As indicated by the STOLPER (1977a) model and by theoretical considerations (PRESNALL, 1969), this would have inhibited further evolution of the system, i.e. the production of more magnesian materials, even if considerable additional heating took place. This course of events would therefore have resulted in the formation of a differentiated series of eucritic rocks and a series of pyroxenitic residues, broadly classifiable as diogenites, in which

the Fe/Fe+Mg (molar) ratio decreased continuously from 0.33 (that of Source Region 2) to about 0.24 (that of the non-Antarctic diogenites); the pyroxenes in such diogenites ranged from those of the most Fe-rich diogenite recorded, Yamato 75032 (En₆₅: TAKEDA et al, 1979b) to those of 'normal' diogenites (about En₇₅: MASON, 1968). Neither the intermediate compositions nor the most magnesian materials observed in howardites would have been produced by this method (see Figs 9.2 and 9.3).

The second alternative depends on the retention in the source region of at least part of the plagioclase-bearing melts formed in the initial stage of the partial melting of the source region. As pointed out by STOLPER (1977a, p. 600), this would enable further partial melting to take place, with the compositions of the liquids changing along the olivine-pyroxene phase boundary away from the location of the 'primary' eucrites and towards the projected position of the source region composition. It is envisaged that the source composition itself had undergone change prior to the start of the second stage of achondrite genesis under consideration. Its projected position depended on the proportion of eucritic melt that had been removed from the source region, but lay on the olivine-pyroxene boundary intermediate between the original source composition (Source Region 2) and the edge of the pseudo-ternary diagram; it is schematically indicated in Fig. 9.2 as Source Region 2', and represents the aggregate composition of the residues from Stage 1 of the proposed model (formation of the eucrites) and trapped eucritic liquid.

It is postulated, therefore, that further heating of the source region after separation of some of the eucritic melt generated in the first melting sequence caused a second stage of partial melting, in this instance of a modified source composition, to occur. The compositional range covered by the second-stage partial melts extends along the olivine-pyroxene boundary

from the peritectic A to the new position of the source composition, at which point complete fusion would have been achieved. This range is roughly that of the howardites (Fig. 5.32). Separation of the second-stage partial melts may have been episodic in character, occurring only (as in the formation of the eucrites) when a critical degree of melting had been reached. The process may have resembled incremental batch melting (COX et al., 1979, p. 73), in which amounts of equilibrium melt are separated from the residuum whenever a critical percentage of fusion is attained. In this way, a series of compositionally discrete liquids decreasing in Fe/Fe+Mg ratio as melting progressed could have been produced. Repetition of the process in different parts of the source region, perhaps under slightly differing physico-chemical conditions, possibly resulted in a fairly continuous range of intermediate compositions being emplaced in the crustal regions of the parent body, where they were available for impact brecciation and eventual incorporation in howardites.

The intermediate liquids produced in the second stage of partial melting crystallized plagioclase in association with primary pigeonite until a composition of about En_{60} was reached. Associated orthopyroxene more Fe-rich than this value appears to have inverted from pigeonite. Primary orthopyroxene and plagioclase co-precipitated in the range En_{60} - En_{67} , but plagioclase was not observed in the crystallization sequence of pyroxenes more magnesian than the latter value. It is significant that pyroxenes of this limiting composition have an Fe/Fe+Mg (molar) ratio of 0.33, identical to that of Source Region 2 (Table 5.12); see Fig. 9.3. This suggests that in some instances almost all the eucritic melt generated in the first stage of partial melting may have been retained in the source region, the bulk composition of which consequently remained approximately unaltered (i.e. = Source Region 2) at the start of the second stage. Conversely, removal of

a significant proportion of feldspar-bearing liquid during the course of eucrite formation resulted in increased divergence between the Fe/Fe+Mg ratios of the point in the pyroxene crystallization sequence at which precipitation of plagioclase ceased and that of the modified source material (Source Region 2').

The compositional range of the residues from the second stage of partial fusion extended from the new source region composition (Source Region 2' in Fig. 9.2) along the olivine-pyroxene phase boundary to arrive at the diogenite field at the edge of the pseudo-ternary diagram simultaneously with the exhaustion of whatever plagioclase remained available for reaction in the source material. With the subtraction of the feldspar phase from the system, the pyroxenitic residues remained on the margin of the pseudo-ternary but underwent a continual decrease in Fe/Fe+Mg ratio because of removal of Fe from the source region - assumed to be a closed system - by the last partial melts to form. In this way, it is suggested, the pyroxenes present in howardites that are more magnesian than those of the diogenites, i.e. in the range En_{75} to En_{86} , were produced.

It will be noted that, in this model proposed for the formation of the achondrites, compositional overlaps may occur in the residues produced by the two stages of partial melting (Figs 9.2 and 9.3). Similarly, there may be overlap in the pyroxene compositions of the cumulate eucrites and of some of the partial melts generated in the second stage (Fig. 9.3), but it should be possible to assign lithic clasts in howardites to the correct formational stage on the combined evidence of texture and bulk composition where such overlap is present (see Fig. 9.2). This distinction may not be so readily made in the regions of overlap in the residual compositions.

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Fig. 9.2. A schematic representation of the genetic processes involved in the formation of the three main classes of achondrites from a source composition present in the outer parts of the parent body. The figure is based on the silica-olivine-anorthite 'pseudo-liquidus' projection of STOLPER (1977a) and Fig. 5.32 of this work, with which it should be compared. The source material corresponds to 5% plagioclase, 90% pyroxene, 5% spinel, and negligible olivine (Source Region 2). Its projected position lies on the olivine-pyroxene phase boundary, and is represented by a filled star. The model discussed in the text proposes that the achondrites were formed by partial melting of the source material in two stages. In Stage 1 (filled arrows), the 'primary' eucrites were formed by small amounts (up to 20%) of partial melting, or by low pressure fractional crystallization of these initial melts; some eucritic cumulates must have resulted from this process. More extensive fractionation of the 'primary' melts (e.g. Sioux County) concentrated near the peritectic A generated residual liquids (e.g. Nuevo Laredo) and corresponding cumulate eucrites (e.g. Moama). The resulting fractionation trends lay along the plagioclase-pyroxene and plagioclase-olivine boundaries respectively, AB' being the path followed by liquids produced by fractional crystallization. The composition of the residues from the first stage of partial fusion moved along the olivine-pyroxene boundary away from Source Region 2 and reached the edge of the projection as feldspar was exhausted from the source. This formed a diogenite series ranging from the most Fe-rich (Yamato 75032) to the 'normal' diogenites. The eucrite series and the diogenites therefore basically originated from the first stage of partial melting. The addition of further heat to the source region initiated Stage 2 (open arrows), provided all the feldspathic melt had not been removed. The new source composition, represented by 2' in the figure, therefore consisted of residual material and trapped liquid, and accordingly occupied a position on the phase boundary between that of the original source and the edge of the pseudo-ternary. Partial melting of this new source material generated a series of intermediate melts which, together with eucritic and diogenitic materials, were eventually incorporated in the howardites, giving rise to the continuous compositional variation in that class. The residues from the second stage of partial melting showed compositional overlap with the diogenite series to the point at which the edge of the diagram was reached, after which the residual pyroxenes continued to be enriched in Mg as a result of removal of Fe by the partial melts. This produced the range of pyroxenes with compositions more magnesian than diogenitic pyroxenes that is present in howardites.

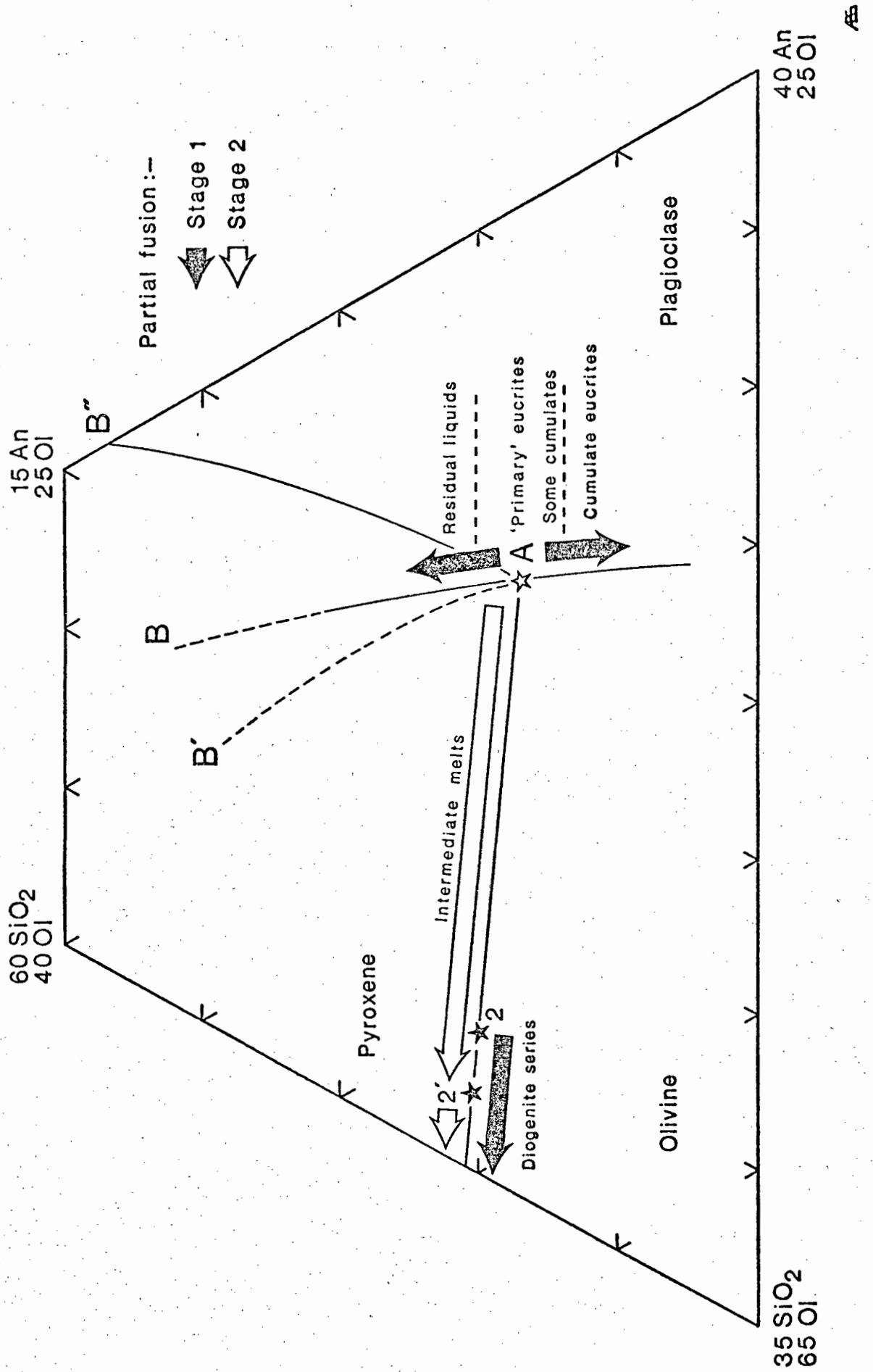
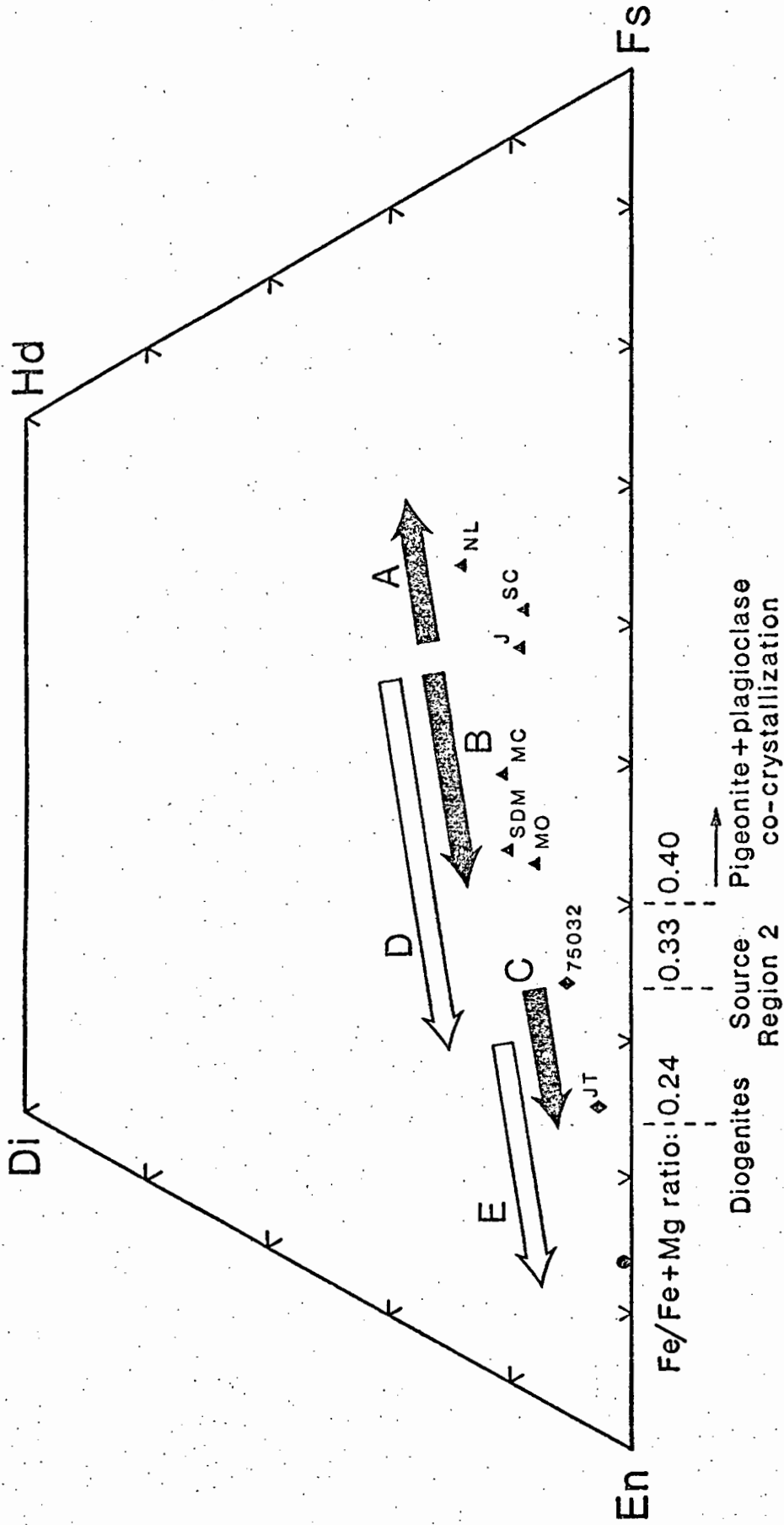


Fig. 9.3. A schematic representation of the trends of compositional variation in achondritic pyroxenes resulting from the formational processes diagrammatically presented in Fig. 9.2. Trends associated with the first stage of partial melting are denoted by filled arrows, while those of the second stage are indicated by open arrows. Trends A and B show the range of pigeonites produced by the low pressure fractionation of 'primary' eucritic melts, here represented by Sioux County and Juvinas. Trend C is that of the diogenitic residues from the production of the eucrite series. It extends from the Antarctic diogenite Yamato 75032 to the non-Antarctic diogenites (as exemplified by Johnstown), and covers a range of bulk Fe/Fe+Mg (molar) values from 0.33 to 0.24. Trend D shows the approximate extent of pyroxene variation in the liquids of intermediate composition formed in the second stage of partial fusion. This trend may be discontinuous in any particular part of the parent body crust but, in combination with other similar trends, probably represents continuous compositional variation in these pyroxenes after regolith formation. The trend extends from the position of the 'primary' eucrites (the peritectic A in Fig. 9.2) to that of the new source composition 2', whose location within the diogenitic range is determined by the amount of trapped feldspathic liquid present in the residues from the first stage of partial melting. The residues from the second stage are represented by Trend E, extending from Source Region 2' to at least En₈₆, the composition of the most magnesian pyroxene analyzed in the present study (filled circle). In these trends, concomitant crystallization of pigeonite and plagioclase appears to cease at about En₆₀, and plagioclase disappears from the crystallization sequence at about En₆₇. Sources of data on pyroxenes: Juvinas, Sioux County, and Nuevo Laredo - TAKEDA et al. (1978a); Moama - LOVERING (1975); Moore County and Serra de Magé - HARLOW et al. (1979); Yamato 75032 - TAKEDA and MIYAMOTO (1977); and Johnstown - FLORAN et al. (1981).



The model proposed therefore envisages the production, by the processes discussed, of a crustal zone in the parent body that included members of the differentiated eucritic series, Mg-rich pyroxenitic residues (some of which were diogenitic), and a range of differentiated rocks, perhaps volumetrically less important than the eucrites and the residues, with compositions intermediate between the 'primary' eucrites and the diogenite series. As suggested earlier, there may have been local variations in the proposed genetic processes; in some parts of the parent body, they may not have progressed beyond the first stage, whereas the process of achondrite formation may have gone to completion in other localities. Considerable overlaps in space and time may have occurred. In essence, however, it is proposed that these processes, through their complex interaction if necessary, resulted in a wide variety of differentiated achondritic materials at the surface, or in the near-surface parts, of the parent body where they were acted on by the agencies discussed in section 9.2.4 to produce not only the meteorites of the three main achondrite classes, but also the mineral and lithic compositions that occur only as clasts in polymict achondritic breccias and have no known meteoritic representatives. The model also contains the possibility, consistent with evidence from oxygen isotope studies and the olivine data of DESNOYERS (1982), of mesosiderites and pallasites having been excavated from deeper zones in the same body.

9.4.3 A comparison with other models of achondrite genesis

The model presented in this work is in some respects innovative, a fact that makes direct comparison with other models somewhat difficult. There can be little common ground, for instance, between the genetic scheme proposed above and one that postulates an origin for the mesosiderites by the mixing of howardites or eucrites and metal, whether from an external or

an internal source (PRIOR, 1918; LOVERING, 1962). Similarly, the model cannot be reconciled with the view that achondrites and mesosiderites originated in different parent bodies (e.g. MITTFEHLDT, 1977, 1978, 1979b; MITTFEHLDT et al., 1979; DELANEY et al., 1980). It departs also from models that derive eucrites and diogenites from a common magma by fractional crystallization (MASON, 1962a; DUKE and SILVER, 1967) because it is based largely on partial melting processes (STOLPER, 1975a and b, 1977a). The results of the studies of the petrography and phase chemistry of the howardites carried out do not support the model of howardite formation by mixture of eucritic and diogenitic end-members of restricted composition, with or without the addition of a chondritic component (JÉROME and GOLES, 1971; McCARTHY et al., 1972; FUKUOKA et al., 1977; and DREIBUS et al., 1977). The genetic model proposed by McCARTHY et al. (1973), in which Binda is considered as a parental liquid from which the eucrites and diogenites fractionated, is also inconsistent with the interpretation put on the data of the present investigation.

The model presented in the preceding section is based on that of STOLPER (1977a), which concentrated on the genesis of the eucrites. This model attempts to modify some of Stolper's conclusions and to extend the general approach adopted by him to the formation of the other major achondrite classes. The main modification proposed - direct derivation of the cumulate eucrites from 'primary' eucritic liquids - finds support in various other studies, e.g. in the modelling of REE by CONSOLMAGNO and DRAKE (1977) and by HAMET et al. (1978), but the original Stolper version has been accepted by a number of writers, e.g. MA and SCHMITT (1979). The extension of the genetic scheme to try to account for the origin of the diogenites and to explain the presence in howardites of constituents not contained in either the eucritic or the diogenitic series is hypothetical and probably simplistic in its approach. A broad picture only could be attempted, but undoubtedly the

genetic processes were complex in detail. For instance, the diogenites - here treated as residues from partial melting - are considered as cumulates by FLORAN et al. (1977, 1981), who also point out that some have undergone recrystallization and some may be polymict. FUKUOKA et al. (1977) and CONSOLMAGNO (1979) encountered difficulties in modelling the diogenites from their REE abundances. These factors indicate a complex formational history for the diogenites either subsequent to, or as an alternative to, the origin proposed by the model presented in this work.

Comparison can be made between specific aspects of this and other models, for instance the composition of the source from which the eucrites were derived, a topic that has received much attention in the literature in recent years, e.g. CONSOLMAGNO and DRAKE (1977); MORGAN et al. (1978). In section 5.10.2, the close similarity of the source composition calculated for the present model from the data of STOLPER (1977a) to the PR* composition of DREIBUS et al. (1977) and to the howardite Yamato 7308 (Table 5.12) was discussed. Later refinement of the model (DREIBUS and WÄNKE, 1980) improved the correspondence of the PR* composition to Source Region 2 of the present model for some oxides while worsening it for others, but these are merely differences in detail. Dreibus and Wänke argued that the refractory lithophile elements are present in the PR* composition in approximately the abundance ratios found in C1 chondrites, i.e. unfractionated primitive matter, and further refined their earlier model by correcting the anomalously low Mg/Si ratio of PR* by the addition of 43% of olivine of the composition found in the pallasite Marjalahti in place of the lunar olivine originally used. This correction enabled them to calculate the bulk composition of the silicate portion of the eucrite parent body; the estimate arrived at shows a close correspondence to Orgueil, a C1 chondrite (DREIBUS and WÄNKE, 1980, Table 2).

The similarity between PR* and the source composition for the eucrites (and other achondrites) used in the present model suggests that this reasoning would apply also to the current study. Unfortunately, the composition calculated for Source Region 2 could include only major elements (Table 5.12), and this limits close comparison of an estimated bulk composition of the parent body with C1 chondrites. However, the principle of addition of pallasitic material in order to obtain such a bulk composition is entirely in keeping with the tentative suggestion made in the present work that the innermost parts of the achondrite body may be pallasitic. The objection raised (DREIBUS et al., 1977; DREIBUS and WÄNKE, 1980) that parent body compositions calculated from the data of STOLPER (1977a) are considerably too high in FeO (e.g. CONSOLMAGNO and DRAKE, 1977) applies only to calculations based on a high modal content of olivine in the source region; no such problem occurs if the alternative offered by Stolper - negligible olivine in the source region - is used, as in the present work (see Table 5.12).

The model developed by the Mainz group (and, as inferred above, the present model also) points to approximately chondritic abundances (except for volatiles) in the parent body. 'This appears to be a general assumption: see, for instance, CONSOLMAGNO and DRAKE (1977) and MORGAN et al. (1978). It is, however, as previously noted, inconsistent with the evidence from oxygen isotope studies (CLAYTON and MAYEDA, 1975; CLAYTON et al., 1976). The present work can contribute nothing to the solution of this dilemma.

It is pertinent to the conclusions reached on the nature of Binda in the present investigation to note that Binda was the only meteorite that had to be discarded from the achondrite modelling calculations of DREIBUS and WÄNKE (1980), who commented (p. 211): "Binda is exceptionally low in all incompatible trace elements."; cf. sections 4.7.2 and 5.7, and CHOU et al. (1976). They concluded that Binda's deviations from their model "indicate

an origin distinctly different from that of all other howardites."

The cumulate nature of the meteorite was confirmed by the positive Eu anomaly revealed by their data.

In a series of publications starting with TAKEDA et al. (1976), Japanese workers have proposed and developed a model for an achondrite parent body in which the crust displays compositional layering. It is essentially a differentiation model based on detailed studies of pyroxene crystallization and the cooling rates that can be deduced therefrom. These studies found that the eucrites could be sub-divided into two types - subsequently termed 'equilibrated' and 'unequilibrated' by REID and BARNARD (1979) - on the basis of compositional differences in their pyroxenes (TAKEDA et al., 1978a). The estimated cooling rates were used to calculate the depths at which known eucrites were formed in the crust of the parent body (MIYAMOTO and TAKEDA, 1977), which was estimated to be about 15km thick. This process was extended by TAKEDA (1979), who defined the six layers present in the crust of the eucrite parent body or, as he proposed that it should more accurately be termed, the howardite parent body. These layers are, from bottom to top: (1) Mg-rich diogenites, (2) Fe-rich diogenites, (3) Binda-like cumulate eucrites, (4) Moore County-like cumulate eucrites, (5) Juvinas-like ('equilibrated') eucrites, and (6) Pasamonte-like ('unequilibrated') surface eucrite layer. MIYAMOTO et al. (1979) proposed that polymict eucritic breccias were more likely to have been the surface materials on the parent body than howarditic breccias because of the lesser content of deep-seated diogenitic material in the eucritic varieties. This suggestion was subsequently amended by TAKEDA et al. (1979a, 1980), who proposed that polymict eucrites were the product of shallow excavation of the layered crust, whereas large impacts were responsible for the deeper excavations that caused diogenitic materials to be incorporated in the howardites. TAKEDA et al. (1980) recognized the

importance of howarditic debris on the planetary surface, and stressed the strong genetic link that exists between howardites and polymict eucrites.

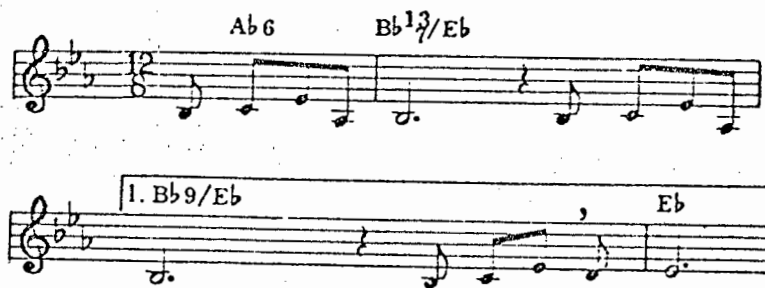
There are points of difference between the Takeda model and that presented in this work. Firstly, the layered crust concept was based originally on pyroxene trends in conditions of fractional crystallization. If the layering is considered to occur in the crust of the entire parent body, widespread complete fusion of the source materials is implied. This is incompatible with the present model, which envisages partial melting as having taken place in varying degrees and probably in widely separated localities in the parent body that increased in number with the passage of time. Under such circumstances, a complete crust may not have been built up. Mesosideritic upper mantle may have been exposed in places, melts of intermediate composition in others, while a capping of eucritic extrusive rocks was probably widespread. Cumulate eucrites occurred deeper in the crust, probably in a sporadic fashion, and pyroxenitic residues were situated wherever partial melting had taken place. But for the meteorite bombardment that produced a planet-wide regolith, the surface of the parent body envisaged by the current model would have presented a somewhat heterogeneous and varied appearance. Secondly, the existence of true cumulate eucrites with pyroxenes as magnesian as those of Binda has yet to be demonstrated (see Fig. 7.8). The present work has shown that Binda is not a cumulate eucrite and has suggested an alternative classification. Thus, if a layer of cumulates with pyroxenes as Mg-rich as those of Binda, i.e. more magnesian than the pyroxenes of the Moore County-like cumulates, did in fact exist, these cumulates would not have borne a close compositional resemblance to Binda. The models are, however, in agreement on the suggested difference in mode of origin of polymict eucrites and howardites (TAKEDA et al., 1979a).

A petrogenetic model proposed by STOLPER et al. (1978, 1979) seeks to establish a relationship between basaltic achondrites, shergottites, nakhlites, and chassignites and is therefore mainly outside the scope of the present investigation. Stolper and his co-workers regarded these four classes of achondrites as defining a petrological and geochemical sequence and proposed that successive modifications of the source material of the basaltic achondrites could provide sources to account for the compositions of the other three classes. The model is based on the assumption that the source material of the basaltic achondrites was an alkali-poor, metal-bearing plagioclase peridotite. Addition of volatile-rich material such as pure Na_2O or a C1 chondrite to this source, or progressive depletion of volatiles in material of approximately C1 composition, were suggested as means by which a series of peridotites parental to the shergottites, nakhlites, and chassignites could have been produced. Because it minimizes the role played by olivine in the formation of the three main classes of achondrite, the model outlined in the present work is not compatible with the basic assumption of a peridotitic source material for the basaltic achondrites made by Stolper and his colleagues.

Differences exist between the present model and concepts stated by some other workers in the field. The model outlined by REID and DUKE (1981) considers the source material from which eucrites were derived to have been representative of the composition of the whole parent body, i.e. the parent body was undifferentiated and had a composition - probably near-chondritic, but depleted in volatiles - acquired at the time of accretion. DELANEY et al. (1980) concluded that howardites and mesosiderites did not originate on the same parent body because of the differences in physical conditions and igneous processes implied by the different behaviour of the FeO/MnO ratios in the olivines of the two types of meteorites. The validity of this

conclusion cannot be assessed from the data of the present study because the phase chemistry of the mesosiderites was not studied and practically no olivines occur in the howardites investigated. However, while conceding the validity of the observations of Delaney and his colleagues, HEWINS (1981) considered they did not constitute proof of separate parent bodies for howardites and mesosiderites. Modal studies of howardites carried out by LABOTKA and PAPIKE (1980) indicated a degree of correspondence between the proportions of orthopyroxenitic and plagioclase-pyroxene clasts present and the amounts of diogenitic and eucritic components calculated from chemical mixing models (McCARTHY et al., 1972; FUKUOKA et al., 1977; and DREIBUS et al., 1977). Because of the range of compositions present in the pyroxenes, these modal studies failed to define a single 'eucritic' source, and concluded that the bulk compositions of the host rocks from which the pyroxenes were derived must lie on a linear trend similar to that of the howardites. This is the contention of the present study also.

REFERENCES



Popular song (1973)

- AGOSTO W.N., HEWINS R.H., and CLARKE R.S. (1980) Allan Hills A77219, the first Antarctic mesosiderite. Proc. Lunar Planet. Sci. Conf. 11th, pp. 1027-1045. Pergamon.
- AHRENS L.H. (1964a) Notes on Na-K fractionation in chondrites. Geochim. Cosmochim. Acta 28, 1869-1870.
- AHRENS L.H. (1964b) Si-Mg fractionation in chondrites. Geochim. Cosmochim. Acta 28, 411-423.
- AHRENS L.H. (1970a) The composition of stony meteorites (VI). a) The Mg-Cr relationship in some basaltic achondrites, Apollo 11 soil and Apollo 12 rock 12038. b) The Ba-Rare Earth relationship in stony meteorites and Apollo 11 rocks and soil. Earth Planet. Sci. Lett. 9, 336-340.
- AHRENS L.H. (1970b) The composition of stony meteorites (VII). The special significance of eucrites Stannern and Nuevo Laredo in lunar-meteorite comparative studies. Earth Planet. Sci. Lett. 9, 341-344.
- AHRENS L.H. (1970c) The composition of stony meteorites (IX). Abundance trends of the refractory elements in chondrites, basaltic achondrites and Apollo 11 fines. Earth Planet. Sci. Lett. 10, 1-6.

- AHRENS L.H. (1976) The distribution of Cr and the Mg-Cr relationship in terrestrial, meteoritic and lunar basalts. Geochem. J. 10, 51-58.
- AHRENS L.H. and DANCHIN R.V. (1970) Lunar surface rocks and fines: chemical composition. Science 167, 87-88.
- AHRENS L.H. and DANCHIN R.V. (1971) The chemical composition of the basaltic achondrites. In Physics and Chemistry of the Earth, (editors L.H. Ahrens, F. Press, and S.K. Runcorn), 8, pp. 265-303. Pergamon.
- AHRENS L.H. and VON MICHAELIS H. (1969a) The composition of stony meteorites (III). Some inter-element relationships. Earth Planet. Sci. Lett. 5, 395-400.
- AHRENS L.H. and VON MICHAELIS H. (1969b) The composition of stony meteorites (V). Some aspects of the composition of the basaltic achondrites. Earth Planet. Sci. Lett. 6, 304-308.
- AHRENS L.H., EDGE R.A., and TAYLOR S.R. (1960) The uniformity of trace elements in chondrites - with particular reference to Cs. Geochim. Cosmochim. Acta 20, 260-272.
- AHRENS L.H., VON MICHAELIS H., ERLANK A.J., and WILLIS J.P. (1968) Fractionation of some abundant lithophile element ratios in chondrites. Earth Planet. Sci. Lett. 5, 45-46.
- ALLÈGRE C.J., BIRCK J.-L., and FOURCADE S. (1973) $^{87}\text{Rb}/^{87}\text{Sr}$ age of Juvinas basaltic achondrite and early igneous activity in the solar system (abstr.). Meteoritics 8, 323.
- ANDERS E. (1978) Most stony meteorites come from the asteroid belt. In Asteroids: An Exploration Assessment, (editors D. Morrison and W.C. Wells), NASA CP-2053, pp. 57-75.
- ANDERSEN O. (1915) The system anorthite-forsterite-silica. Amer. J. Sci. 39, 407-454.
- ANDERSON C. and MINGAYE J.C.H. (1913) Description and analysis of the Binda

- meteorite. Rec. Aust. Mus. 10, 49-52.
- AXON H.J. and NASIR M.J. (1977) A metallographic and microprobe examination of a metallic nodule from the Bondoc Peninsula meteorite. Mineral. Mag. 41, M1-3.
- BAIRD A.K. (1961) A pressed-specimen die for the Norelco vacuum-path X-ray spectrograph. Norelco Reporter 8, 108-109.
- BARTH T.F.W. (1962) Theoretical Petrology (2nd edition). 416 pp. Wiley.
- BEGEMANN F., WEBER H.W., VILCSEK E., and HINTENBERGER H. (1976) Rare gases and ^{36}Cl in stony-iron meteorites: cosmogenic elemental production rates, exposure ages, diffusion losses, and thermal histories. Geochim. Cosmochim. Acta 40, 353-368.
- BENCE A.E. and ALBEE A.L. (1968) Empirical correction factors for the electron microanalysis of silicates and oxides. J. Geol. 76, 382-403.
- BENCE A.E., DELANO J.W., PAPIKE J.J., and CAMERON K.L. (1974) Petrology of the highlands massifs at Taurus-Littrow: an analysis of the 2-4mm soil fraction. Proc. Lunar Sci. Conf. 5th, pp. 785-827. Pergamon.
- BENCE A.E., GROVE T.L., and PAPIKE J.J. (1980) Basalts as probes of planetary interiors: constraints on the chemistry and mineralogy of their source. Precamb. Res. 10, 249-279.
- BILD R., SCHAUDY R., CHOU C.-L., BAEDECKER P.A., and WASSON J.T. (1973) Mesosiderites: a search for fractionation trends (abstr.). Meteoritics 8, 14.
- BIRCH G.F. (1979) The nature and origin of mixed apatite/glaucinite pellets from the continental shelf off South Africa. Marine Geol. 29, 313-334.
- BIRCK J.-L. and ALLÈGRE C.J. (1978a) Chronology and chemical history of the parent body of basaltic achondrites studied by the ^{87}Rb - ^{87}Sr method. Earth Planet. Sci. Lett. 39, 37-51.
- BIRCK J.-L. and ALLÈGRE C.J. (1978b) $^{87}\text{Rb}/^{87}\text{Sr}$ study of some diogenites and

- the Binda howardite (abstr.). Meteoritics **13**, 394.
- BIRCK J.-L. and ALLÈGRE C.J. (1979) ^{87}Rb - ^{87}Sr chronology of the Binda howardite. Nature **282**, 288-289.
- BIRCK J.-L. and ALLÈGRE C.J. (1981) $^{87}\text{Rb}/^{87}\text{Sr}$ study of diogenites. Earth Planet. Sci. Lett. **55**, 116-122.
- BOYD F.R., FINGER L.W., and CHAYES F. (1968) Computer reduction of electron-probe data. Carnegie Inst. Wash. Yearb. 1967, 210-215.
- BROWNLEE D.E. and RAJAN R.S. (1973) Micrometeorite craters discovered on chondrule-like objects from Kapoeta meteorite. Science **182**, 1341-1344.
- BRUSH G.J. (1869) On the meteoric stone which fell December 5, 1868, in Franklin Co., Alabama. Amer. J. Sci. **48**, 240-244.
- BRYAN W., FINGER L., and CHAYES F. (1969) Estimating proportions in petrogenic mixing equations by least squares approximation. Science **163**, 926-927.
- BUNCH T.E. (1975) Petrography and petrology of basaltic achondrite polymict breccias (howardites). Proc. Lunar Sci. Conf. 6th, pp. 469-492. Pergamon.
- BUNCH T.E. and KEIL K. (1971) Chromite and ilmenite in non-chondritic meteorites. Amer. Mineral. **56**, 146-157.
- BUNCH T.E., CHANG S., NEIL J.M., and BURLINGAME A. (1976) Unique characteristics of the Jodzie howardite (abstr.). Meteoritics **11**, 260-261.
- BUNCH T.E., COHEN A.J., and DENCE M.R. (1967) Natural terrestrial maskelynite. Amer. Mineral. **52**, 244-253.
- BUSCHE F.D., PRINZ M., KEIL K., and BUNCH T.E. (1972) Spinel and the petrogenesis of some Apollo 12 igneous rocks. Amer. Mineral. **57**, 1729-1747.
- CAMERON E.N. (1971) Opaque minerals in certain lunar rocks from Apollo 12. Proc. Lunar Sci. Conf. 2nd, pp. 193-206. M.I.T. Press.

- CARDOSO M.P.A. (1980) A study of mantle inclusions in the Koffiefontein kimberlite pipe, South Africa. M.Sc. thesis, University of Cape Town. 133 pp.
- CARMICHAEL I.S.E., TURNER F.J., and VERHOOGEN J. (1974) Igneous Petrology. 739 pp. McGraw-Hill.
- CHAO E.C.T. (1967) Impact metamorphism. In Researches in Geochemistry, (editor P.H. Abelson), Vol. 2, pp. 204-233. John Wiley.
- CHAPMAN C. (1976) Asteroids as meteorite parent-bodies: the astronomical perspective. Geochim. Cosmochim. Acta 40, 701-719.
- CHERRY R.D., HOBBS J.B.M., ERLANK A.J. and WILLIS J.P. (1970) Thorium, uranium, potassium, lead, strontium and rubidium in silicate rocks by gamma-spectroscopy and/or X-ray fluorescence. Can. Spectrosc. 15, 3-9, 16.
- CHLADNI E.F.F. (1794) Über den Ursprung der von Pallas gefundenen und anderer ihr ähnlicher Eisenmassen und über einige damit in Verbindung stehende Naturerscheinungen. 63 pp. Hartknoch.
- CHOU C.-L., BOYNTON W.V., BILD R.W., KIMBERLIN J., and WASSON J.T. (1976) Trace element evidence regarding a chondritic component in howardite meteorites. Proc. Lunar Sci. Conf. 7th, pp. 3501-3518. Pergamon.
- CLARKE R.S., JAROSEWICH E., MASON B., NELEN J., GOMEZ M., and HYDE J.R. (1970) The Allende, Mexico, meteorite shower. Smithsonian Contrib. Earth Sci. 5, 1-53.
- CLAYTON R.N. and MAYEDA T.K. (1975) Genetic relations between the Moon and meteorites. Proc. Lunar Sci. Conf. 6th, pp. 1761-1769. Pergamon.
- CLAYTON R.N. and MAYEDA T.K. (1978a) Genetic relations between iron and stony meteorites. Earth Planet. Sci. Lett. 40, 168-174.
- CLAYTON R.N. and MAYEDA T.K. (1978b) Multiple parent bodies of polymict brecciated meteorites. Geochim. Cosmochim. Acta 42, 325-327.
- CLAYTON R.N., GROSSMAN L., and MAYEDA T.K. (1973) A component of primitive nuclear composition in carbonaceous meteorites. Science 182, 485-488.

- CLAYTON R.N., ONUMA N., and MAYEDA T.K. (1976) A classification of meteorites based on oxygen isotopes. Earth Planet. Sci. Lett. 30, 10-18.
- CONSOLMAGNO G.J. (1979) REE patterns versus the origin of the basaltic achondrites. Icarus 40, 522-530.
- CONSOLMAGNO G.J. and DRAKE M.J. (1977) Composition and evolution of the eucrite parent body: evidence from rare earth elements. Geochim. Cosmochim. Acta 41, 1271-1282.
- COX K.G., BELL J.D., and PANKHURST R.J. (1979) The Interpretation of Igneous Rocks. 450 pp. Allen and Unwin.
- CRAWFORD M.L. (1973) Crystallization of plagioclase in mare basalts. Proc. Lunar Sci. Conf. 4th, pp. 705-717. Pergamon.
- CROZAZ G. (1978) Thermal history of the mesosiderite Estherville revisited (abstr.). Meteoritics 13, 429.
- DALE T.M. and HENDERSON P. (1972) The partition of transition elements in phenocryst-bearing basalts and their implications about melt structure. Rep. 24th Int. Geol. Congr., Sect. 10, 105-111.
- DALY R.A. (1943) Meteorites and an Earth-model. Bull. Geol. Soc. Amer. 54, 401-456.
- DEER W.A., HOWIE R.A. and ZUSSMAN J. (1966) An Introduction to the Rock-Forming Minerals. 528 pp. Longmans.
- DEGEWIJ J., TEDESCO E.F., and ZELLNER B. (1979) Albedo and color contrasts on asteroid surfaces. Icarus 40, 364-374.
- DELANEY J.S., NEHRU C.E., and PRINZ M. (1980) Olivine clasts from mesosiderites and howardites: clues to the nature of achondritic parent bodies. Proc. Lunar Planet. Sci. Conf. 11th, pp. 1073-1087. Pergamon.
- DESNOYERS C. (1982) L'olivine dans les howardites: origine, et implications pour le corps parent de ces météorites achondritiques. Geochim. Cosmochim. Acta 46, 667-680.

- DESNOYERS C. and JÉROME D.Y. (1973) Olivine compositions in howardites and other achondritic meteorites (abstr.). Meteoritics **8**, 344-345.
- DESNOYERS C. and JÉROME D.Y. (1974) Composition chimique des verres de la météorite de Bununu. Compt. Rend. Acad. Sci. Paris **278**, sér. D, 3275-3277.
- DESNOYERS C. and JÉROME D.Y. (1975) Malvern howardite: partial solutions of a puzzle (abstr.). Meteoritics **10**, 392.
- DESNOYERS C. and JÉROME D.Y. (1977) The Malvern howardite: a petrological and chemical discussion. Geochim. Cosmochim. Acta **41**, 81-86.
- DEUSER W.G. (1968) Iron-magnesium-aluminium relationships in achondrites. Chem. Geol. **3**, 81-87.
- DREIBUS G. and WÄNKE H. (1980) The bulk composition of the eucrite parent asteroid and its bearing on planetary evolution. Z. Naturforsch. **35a**, 204-216.
- DREIBUS G., KRUSE H., SPETTEL B., and WÄNKE H. (1977) The bulk composition of the Moon and the eucrite parent body. Proc. Lunar Sci. Conf. **8th**, pp. 211-227. Pergamon.
- DUKE M.B. (1963) Petrology of the basaltic achondrite meteorites. Ph.D. thesis, California Institute of Technology. 362 pp.
- DUKE M.B. (1965) Metallic iron in basaltic achondrites. J. Geophys. Res. **70**, 1523-1527.
- DUKE M.B. (1969) Surveyor alpha-scattering data: consistency with lunar origin of eucrites and howardites. Science **165**, 515-517.
- DUKE M.B. (1978) Aïoun el Atrouss: evidence for thermal recrystallization of a eucrite breccia (abstr.). Meteoritics **13**, 443-448.
- DUKE M.B. and SILVER L.T. (1967) Petrology of eucrites, howardites and mesosiderites. Geochim. Cosmochim. Acta **31**, 1637-1665.
- DUNCAN A.R., SHER M.K., ABRAHAM Y.C., ERLANK A.J., WILLIS J.P., and AHRENS

- L.H. (1975) Interpretation of the compositional variability of Apollo 15 soils. Proc. Lunar Sci. Conf. 6th, pp. 2309-2320. Pergamon.
- DUNCUMB P. and JONES E.M. (1969) Electron-probe microanalysis. An easy-to-use computer programme for correcting quantitative data. T.I. Rep. 260. Tube Investments Res. Lab., Saffron Walden, England.
- DYMEK R.F., ALBEE A.L., CHODOS A.A., and WASSERBURG G.J. (1976) Petrography of isotopically-dated clasts in the Kapoeta howardite and petrologic constraints on the evolution of its parent planet. Geochim. Cosmochim. Acta 40, 1115-1130.
- EHMANN W.D. and REBAGAY T.V. (1970) Zirconium and hafnium in meteorites by activation analysis. Geochim. Cosmochim. Acta 34, 649-658.
- EL GORESY A., RAMDOHR P., and MEDENBACH O. (1973) Lunar samples from Descartes site: opaque mineralogy and geochemistry. Proc. Lunar Sci. Conf. 4th, pp. 733-750. Pergamon.
- EL GORESY A., TAYLOR L.A., and RAMDOHR P. (1972) Fra Mauro crystalline rocks: mineralogy, geochemistry and subsolidus reduction of the opaque minerals. Proc. Lunar Sci. Conf. 3rd, pp. 333-349. M.I.T. Press.
- FAIRBAIRN H.W., SCHLECHT W.G., STEVENS R.E., DENNEN W.H., AHRENS L.H., and CHAYES F. (1951) A co-operative investigation of precision and accuracy in chemical, spectrochemical and modal analysis of silicate rocks. U.S. Geol. Surv. Bull. 980.
- FARRINGTON O.C. (1911) Analyses of stone meteorites. Field Mus. Natl Hist. Publ. 151, 195-228.
- FISH R.A., GOLES G.G., and ANDERS E. (1960) The record in the meteorites. III. On the development of meteorites in asteroidal bodies. Astrophys. J. 132, 243-258.
- FISHER D.E. (1973) Achondritic uranium. Earth Planet Sci. Lett. 20, 151-156.
- FLORAN R.J. (1978) Silicate petrography, classification, and origin of the

- mesosiderites: review and new observations. Proc. Lunar Planet. Sci. Conf. 9th, pp. 1053-1081. Pergamon.
- FLORAN R.J., CAULFIELD J.B.D., HARLOW G.E., and PRINZ M. (1978) Impact-melt origin for the Simondium, Pinnaroo, and Hainholz mesosiderites: Implications for impact processes beyond the earth-moon system. Proc. Lunar Planet. Sci. Conf. 9th, pp. 1083-1114. Pergamon.
- FLORAN R.J., PRINZ M., HLAVA P.F., KEIL K., SPETTEL B., and WÄNKE H. (1977) The Johnstown orthopyroxenite (diogenite) and its relationship to meteoritic cumulates (abstr.). Meteoritics 12, 226-227.
- FLORAN R.J., PRINZ M., HLAVA P.F., KEIL K., SPETTEL B., and WÄNKE H. (1981) Mineralogy, petrology, and trace element geochemistry of the Johnstown meteorite: a brecciated orthopyroxenite with siderophile and REE-rich components. Geochim. Cosmochim. Acta 45, 2385-2391.
- FOSHAG W.F. (1938) Petrology of the Pasamonte, New Mexico, meteorite. Amer. J. Sci. 35, 374-382.
- FREDRIKSSON K. and KEIL K. (1963) The light-dark structure in the Pantar and Kapoeta stone meteorites. Geochim. Cosmochim. Acta 27, 717-739.
- FREDRIKSSON K. and KRAUT F. (1967) Impact glass in the Cachari eucrite. Geochim. Cosmochim. Acta 31, 1701-1704.
- FREDRIKSSON K., NOONAN A., BRENNER P., and SUDRE C. (1976) Bulk and major phase composition of eight hypersthene achondrites (abstr.). Meteoritics 11, 278-280.
- FRICK C. and HAMMERBECK E.C.I. (1973) Catalogue of South African and South West African meteorites. Bull. Geol. Surv. S. Afr. 57, 47 pp.
- FROST M.J. (1971) The Molteno meteorite. Mineral. Mag. 38, 89-93.
- FUCHS L.H. (1969) The phosphate mineralogy of meteorites. In Meteorite Research, (editor P.M. Millman), pp. 683-695. D. Reidel Publ. Co.
- FUKUOKA T., BOYNTON W.V., MA M.-S., and SCHMITT R.A. (1977) Genesis of

- howardites, diogenites and eucrites. Proc. Lunar Sci. Conf. 8th, pp. 187-210. Pergamon.
- GANAPATHY R. and ANDERS E. (1969) Ages of calcium-rich achondrites - II. Howardites, nakhlites, and the Angra dos Reis angrite. Geochim. Cosmochim. Acta 33, 775-787.
- GANAPATHY R., KEAYS R.R., LAUL J.C., and ANDERS E. (1970) Trace elements in Apollo 11 lunar rocks: implications for meteorite influx and origin of Moon. Proc. Apollo 11 Lunar Sci. Conf., pp. 1117-1142. Pergamon.
- GARCIA D.J. and PRINZ M. (1978) The Binda orthopyroxene cumulate eucrite (abstr.). Meteoritics 13, 473.
- GAST P.W. (1962) The isotopic composition of strontium and the age of stone meteorites - I. Geochim. Cosmochim. Acta 26, 927-943.
- GAST P.W. (1965) Terrestrial ratio of potassium to rubidium and the composition of Earth's mantle. Science 147, 858-860.
- GOLDSTEIN I. and YAKOWITZ H. (1971) Metallic inclusions and metal particles in the Apollo 12 lunar soil. Proc. Lunar Sci. Conf. 2nd, pp. 177-191. M.I.T. Press.
- GOLES G.G., FISH R.A., and ANDERS E. (1960) The record in the meteorites - I. The former environment of stone meteorites as deduced from K^{40} - Ar^{40} ages. Geochim. Cosmochim. Acta 19, 177-195.
- GOOLEY R.C. (1972) The chemistry and mineralogy of the diogenites. Ph.D. thesis, Arizona State University. 198 pp.
- GOOLEY R.C. and MOORE C.B. (1976) Native metal in diogenite meteorites. Amer. Mineral. 61, 373-378.
- GÖPEL C. and WÄNKE H. (1978) Trace elements in single pyroxene crystals of diogenites, howardites and eucrites (abstr.). Meteoritics 13, 477-480.
- GOSE W.A. (editor) (1974) Glossary of lunar terms. Proc. Lunar Sci. Conf. 5th, Vol. 1, i-xi.

- GREENLAND L.P. (1970) An equation for trace element distribution during magmatic crystallization. Amer. Mineral. 55, 455-465.
- GROSSMAN L. and LARIMER J.W. (1974) Early chemical history of the solar system. Rev. Geophys. Space Phys. 12, 71-101.
- GROVE T.L. and BENCE A.E. (1977) Experimental study of pyroxene-liquid interaction in quartz-normative basalt 15597. Proc. Lunar Sci. Conf. 8th, pp. 1549-1579. Pergamon.
- GROVE T.L. and BENCE A.E. (1979) Crystallization kinetics in a multiply saturated basalt magma: an experimental study of Luna 24 ferrobasalt. Proc. Lunar Planet. Sci. Conf. 10th, pp. 439-478. Pergamon.
- GROVE T.L. and VANIMAN D.T. (1978) Experimental petrology of very low Ti (VLT) basalts. In Mare Crisium: The View from Luna 24, (editors R.B. Merrill and J.J. Papike), pp. 445-471. Pergamon.
- HAMET J., NAKAMURA N., UNRUH D.M., and TATSUMOTO M. (1978) Origin and history of the adcumulate eucrite Moama as inferred from REE abundances, Sm-Nd and U-Pb systematics. Proc. Lunar Planet. Sci. Conf. 9th, pp. 1115-1136. Pergamon.
- HARLOW G.E., NEHRU C.E., PRINZ M., TAYLOR G.J., and KEIL K. (1979) Pyroxenes in Serra de Magé: cooling history in comparison with Moama and Moore County. Earth Planet. Sci. Lett. 43, 173-181.
- HARTUNG J.B., HÖRZ F., and GAULT D.E. (1972) Lunar microcraters and interplanetary dust. Proc. Lunar Sci. Conf. 3rd, pp. 2735-2753. M.I.T. Press.
- HAUGHTON S.H. and PARTRIDGE F.L. (1938) The meteorite fall of Macibini, Zululand. Trans. Geol. Soc. S. Afr. 41, 205-210.
- HEIKEN G.H. (1975) Petrology of lunar soils. Rev. Geophys. Space Phys. 13, (4), 567-587.
- HESS H.H. and HENDERSON E.P. (1949) The Moore County meteorite: a further

- study with comment on its primordial environment. Amer. Mineral. 34, 494-507.
- HEWINS R.H. (1978) The composition and origin of kamacite in howardites (abstr.). Meteoritics 13, 494.
- HEWINS R.H. (1979a) The composition and origin of metal in howardites. Geochim. Cosmochim. Acta 43, 1663-1673.
- HEWINS R.H. (1979b) The pyroxene chemistry of four mesosiderites. Proc. Lunar Planet. Sci. Conf. 10th, pp. 1109-1125. Pergamon.
- HEWINS R.H. (1981) Orthopyroxene-olivine assemblages in diogenites and mesosiderites. Geochim. Cosmochim. Acta 45, 123-126.
- HEWINS R.H. and GOLDSTEIN J.I. (1975) The provenance of metal in anorthositic rocks. Proc. Lunar Sci. Conf. 6th, pp. 343-362. Pergamon.
- HEWINS R.H. and KLEIN L.C. (1978) Provenance of metal and melt rock textures in the Malvern howardite. Proc. Lunar Planet. Sci. Conf. 9th, pp. 1137-1156. Pergamon.
- HEWINS R.H., KULPECZ A.A., PRINZ M., and FLORAN R.J. (1977) Preliminary observations on metal-silicate relations in the Emery mesosiderite (abstr.). Meteoritics 12, 254-257.
- HEY M.H. (1966) Catalogue of Meteorites (3rd edition). 637 pp. British Museum (Natural History).
- HEYMANN D., MAZOR E., and ANDERS E. (1968) Ages of calcium-rich achondrites - I. Eucrites. Geochim. Cosmochim. Acta 32, 1241-1268.
- HEYMANN D., MAZOR E., and ANDERS E. (1969) Ages of the Ca-rich achondrites. In Meteorite Research, (editor P.M. Millman), pp. 444-457. D. Reidel Publ. Co.
- HOLLISTER L.S., TRZCIENSKI W.E., HARGRAVES R.B., and KULICK C.G. (1971) Petrogenetic significance of pyroxenes in two Apollo 12 samples. Proc. Lunar Sci. Conf. 2nd, pp. 529-557. M.I.T. Press.

- HOSTETLER C.J. and DRAKE M.J. (1978) Quench temperatures of Moore County and other eucrites: residence time on eucrite parent body. Geochim. Cosmochim. Acta 42, 517-522.
- HOUSEN K.R. (1976) A model of regolith formation on asteroids (abstr.). Meteoritics 11, 300-301.
- HOUSEN K.R., WILKENING L.L., and GREENBERG R.J. (1978) Why gas-rich meteorites differ from lunar breccias (abstr.). Meteoritics 13, 495.
- HOVEY E.O. (1925) A new meteoric stone from Johnstown, Weld County, Colorado. (With supplemental notes by George P. Merrill and Earl V. Shannon). Amer. Mus. Novitates No. 203. 13 pp.
- HUTCHISON R. (1972) The Angra dos Reis (stone) mineral assemblage and the genesis of stony meteorites. Nature Phys. Sci. 240, 58-59.
- HUTCHISON R., BEVAN A.W.R., and HALL J.M. (1977) Appendix to the Catalogue of Meteorites. 297 pp. British Museum (Natural History).
- ISHII T. and TAKEDA H. (1974) Inversion, decomposition, and exsolution phenomena of terrestrial and extraterrestrial pigeonites. Geol. Soc. Japan Mem. 11, 19-36.
- ISHII T., MIYAMOTO M., and TAKEDA H. (1976) Pyroxene geothermometry and crystallization, sub-solidus equilibration temperatures of lunar and achondritic pyroxenes (abstr.). In Lunar Science VII, pp. 408-410. The Lunar Science Institute, Houston.
- JAIN A.V. and LIPSCHUTZ M.E. (1973) Shock history of mesosiderites. Nature Phys. Sci. 242, 26-28.
- JAMES O.B. (1976) Petrology of aphanitic lithologies in consortium breccia 73215. Proc. Lunar Sci. Conf. 7th, pp. 2145-2178. Pergamon.
- JAROSEWICH E. and MASON B. (1969) Chemical analyses with notes on one mesosiderite and seven chondrites. Geochim. Cosmochim. Acta 33, 411-416.

- JÉROME D.Y. (1970) Composition and origin of some achondritic meteorites. Ph.D. thesis, University of Oregon. 166 pp.
- JÉROME D.Y. (1971) The Malvern meteorite - a comparison with other achondrite breccias (abstr.). Meteoritics 6, 280.
- JÉROME D.Y. and CHRISTOPHE MICHEL-LÉVY M. (1971) Quelques aspects remarquables de la météorite achondritique de Malvern (Afrique du Sud). Bull. Soc. Fr. Minéral. Cristallogr. 94, 156-161.
- JÉROME D.Y. and CHRISTOPHE MICHEL-LÉVY M. (1972) The Washougal meteorite. Meteoritics 7, 449-461.
- JÉROME D.Y. and DESNOYERS C. (1974) Electron microprobe study of glasses in the Bununu and Malvern achondritic meteorites (abstr.). Meteoritics 9, 354-355.
- JÉROME D.Y. and GOLES G.G. (1971) A re-examination of relationships among pyroxene-plagioclase achondrites. In Activation Analysis in Geochemistry and Cosmochemistry, (editors A.O. Brunfelt and E. Steinnnes), pp. 261-266. Universitetsforlaget, Oslo.
- KEIL K. (1969) Meteorite composition. In Handbook of Geochemistry, (editor K.H. Wedepohl), Vol. 1, pp. 78-115. Springer-Verlag.
- KEIL K., BUNCH T.E., and PRINZ M. (1970) Mineralogy and composition of Apollo 11 lunar samples. Proc. Apollo 11 Lunar Sci. Conf., pp. 561-598. Pergamon.
- KIEFFER S.W., SCHAAL R.B., GIBBONS R., HÖRZ F., MILTON D.J., and DUBE A. (1976) Shocked basalt from Lunar Impact Crater, India, and experimental analogues. Proc. Lunar Sci. Conf. 7th, pp. 1391-1412. Pergamon.
- KIRSTEN T. and HORN P. (1977) ³⁹Ar-⁴⁰Ar dating of basalts and rock breccias from Apollo 17 and the Malvern achondrite. Soviet-American Conf. Cosmochem. Moon and Planets (NASA SP-370), Vol. 2, pp. 525-540.

- KLEIN L.C. and HEWINS R.H. (1979) Origin of impact melt rocks in the Bununu howardite. Proc. Lunar Planet. Sci. Conf. 10th, pp. 1127-1140. Pergamon.
- KORRINGA M.K. and NOBLE D.C. (1971) Distribution of Sr and Ba between natural feldspar and igneous melt. Earth Planet. Sci. Lett. 11, 147-151.
- KULPECZ A.A. and HEWINS R.H. (1978) Cooling rate based on schreibersite growth for the Emery mesosiderite. Geochim. Cosmochim. Acta 42, 1495-1500.
- LABOTKA T.C. and PAPIKE J.J. (1980) Howardites: samples of the regolith of the eucrite parent-body: petrology of Frankfort, Pavlovka, Yurtuk, Malvern, and ALHA 77302. Proc. Lunar Planet. Sci. Conf. 11th, pp. 1103-1130. Pergamon.
- LACROIX A. (1926) L'eucrite de Béréba (Haute-Volta) et les météorites feldspathiques en général. Arch. Museum Hist. Nat. Paris, sér. 6, 1, 15-58.
- LACROIX A. (1932) La météorite (diogénite) de Tatahouine, Tunisie (27 juin 1931). Bull. Soc. Fr. Minéral. Cristallogr. 55, 101-122.
- LANGMUIR C.H., VOCKE R.D., HANSON G.N., and HART S.R. (1978) A general mixing equation with applications to Icelandic basalts. Earth Planet. Sci. Lett. 37, 380-392.
- LARSON H.P. and FINK U. (1975) Infra-red spectral observations of asteroid 4 Vesta. Icarus 26, 420-427.
- LAUL J.C., WAKITA H., SHOWALTER D.L., BOYNTON W.V., and SCHMITT R.A. (1972) Bulk, rare earth, and other trace elements in Apollo 14 and 15 and Luna 16 samples. Proc. Lunar Sci. Conf. 3rd, pp. 1181-1200. M.I.T. Press.
- LE ROEX A.P. (1980) Geochemistry and mineralogy of selected Atlantic Ocean basalts. Ph.D. thesis, University of Cape Town. 281 pp.

- LINDSTROM D.J. (1976) Experimental study of the partitioning of the transition metals between clinopyroxene and coexisting silicate liquids. Ph.D. thesis, University of Oregon. 188 pp.
- LOMENA I.S.M., TOURÉ F., GIBSON E.K., CLANTON U.S., and REID A.M. (1976) Aïoun el Atrouss: a new hypersthene achondrite with eucritic inclusions. Meteoritics 11, 51-57.
- LONGHI J., WALKER D., and HAYS J.F. (1978) The distribution of Fe and Mg between olivine and lunar basaltic liquids. Geochim. Cosmochim. Acta 42, 1545-1558.
- LONGHI J., WALKER D., GROVE T.L., STOLPER E.M., and HAYS J.F. (1974) The petrology of the Apollo 17 mare basalts. Proc. Lunar Sci. Conf. 5th, pp. 447-469. Pergamon.
- LOVERING J.F. (1959) The magnetic field in a primary meteorite body. Amer. J. Sci. 257, 271-275.
- LOVERING J.F. (1962) The evolution of the meteorites - evidence for the co-existence of chondritic, achondritic and iron meteorites in a typical parent meteorite body. In Researches on Meteorites, (editor C.B. Moore), pp. 179-197. John Wiley.
- LOVERING J.F. (1964) Electron microprobe analysis of the metallic phase in basic achondrites. Nature 203, 70.
- LOVERING J.F. (1975) The Moama eucrite - a pyroxene-plagioclase adcumulate. Meteoritics 10, 101-114.
- LUGMAIR G.W., MARTI K., KURTZ J.P., and SCHEININ N.B. (1976) History and genesis of lunar troctolite 76535 or: How old is old? Proc. Lunar Sci. Conf. 7th, pp. 2009-2033. Pergamon.
- LUGMAIR G.W., SCHEININ N.B., and CARLSON R.W. (1977) Sm-Nd systematics of the Serra de Magé eucrite (abstr.). Meteoritics 12, 300-301.
- MA M.-S. and SCHMITT R.A. (1979) Genesis of the cumulate eucrites Serra de

- Magé and Moore County: a geochemical study. Meteoritics **14**, 81-89.
- MA M.-S., MURALI A.V., and SCHMITT R.A. (1977) Genesis of the Angra dos Reis and other achondritic meteorites. Earth Planet. Sci. Lett. **35**, 331-346.
- McCALL G.J.H. (1966) The petrology of the Mount Padbury mesosiderite and its achondrite enclaves. Mineral. Mag. **35**, 1029-1060.
- McCALLUM I.S. (1968) Equilibrium relationships among the co-existing minerals in the Stillwater Complex, Montana. Ph.D. thesis, University of Chicago.
- McCARTHY T.S. (1971) Aspects of the chemistry of some stony meteorites. M.Sc. thesis, University of Cape Town. 123 pp.
- McCARTHY T.S. and AHRENS L.H. (1971) The composition of stony meteorites (X). The Ca/Al ratio in mesosiderites. Earth Planet. Sci. Lett. **11**, 35-36.
- McCARTHY T.S., AHRENS L.H., and ERLANK A.J. (1972) Further evidence in support of the mixing model for howardite origin. Earth Planet. Sci. Lett. **15**, 86-93.
- McCARTHY T.S., ERLANK A.J., and WILLIS J.P. (1973) On the origin of eucrites and diogenites. Earth Planet. Sci. Lett. **18**, 433-442.
- McCARTHY T.S., ERLANK A.J., WILLIS J.P., and AHRENS L.H. (1974) New chemical analyses of six achondrites and one chondrite. Meteoritics **9**, 215-221.
- McCORD T.B., ADAMS J.B., and JOHNSON T.V. (1970) Asteroid Vesta: spectral reflectivity and compositional implications. Science **168**, 1445-1447.
- McKAY D.S., HEIKEN G.H., TAYLOR R.M., CLANTON U.S., MORRISON D.A., and LADLE G.H. (1972) Apollo 14 soils: size distribution and particle types. Proc. Lunar Sci. Conf. 3rd, pp. 983-994. M.I.T. Press.
- MALISSA H. (1974) Electron microprobe analysis of some minor and accessory components in mesosiderites. Tschermaks Miner. Petrogr. Mitt. **21**, 233-245.
- MANHES G. and ALLÈGRE C.J. (1978) Time differences as determined from the

ratio of lead 207 to lead 206 in concordant meteorites (abstr.).

Meteoritics 13, 543-548.

MARSHALL R.R. (1968) Lead-lead age of the Bondoc meteorite. Geochim.

Cosmochim. Acta 32, 1013-1018.

MASON B. (1960) The origin of meteorites. J. Geophys. Res. 65, 2965-2970.

MASON B. (1962a) Meteorites. 274 pp. John Wiley.

MASON B. (1962b) The minerals of meteorites. In Researches on Meteorites,
(editor C.B. Moore), pp. 145-163. John Wiley.

MASON B. (1963) The hypersthene achondrites. Amer. Mus. Novitates No. 2155.
13 pp.

MASON B. (1967) The Bununu meteorite, and a discussion of the pyroxene-
plagioclase achondrites. Geochim. Cosmochim. Acta 31, 107-115.

MASON B. (1968) Pyroxenes in meteorites. Lithos 1, 1-11.

MASON B. (editor) (1971) Handbook of Elemental Abundances in Meteorites.
555 pp. Gordon and Breach.

MASON B. (1972a) The mineralogy of meteorites. Meteoritics 7, 309-326.

MASON B. (1972b) Lunar tridymite and cristobalite. Amer. Mineral. 57,
1530-1535.

MASON B. (1974) Notes on Australian meteorites. Rec. Aust. Mus. 29, 169-186.

MASON B. and JAROSEWICH E. (1971) The composition of the Johnstown meteorite.
Meteoritics 6, 241-245.

MASON B. and JAROSEWICH E. (1973) The Barea, Dyarri Island, and Emery
meteorites, and a review of the mesosiderites. Mineral. Mag. 39,
204-215.

MASON B. and MELSON W.G. (1970) Comparison of lunar rocks with basalts and
stony meteorites. Proc. Apollo 11 Lunar Sci. Conf., pp. 661-671.
Pergamon.

MASON B. and WILK H.B. (1966a) The composition of the Barratta, Carraweena,

- Kapoeta, Mooresfort and Ngawi meteorites. Amer. Mus. Novitates
No. 2273. 25 pp.
- MASON B. and WIIK H.B. (1966b) The composition of the Bath, Frankfort,
Kakangari, Rose City, and Tadjera meteorites. Amer. Mus. Novitates
No. 2272. 24 pp.
- MASON B., JAROSEWICH E., and NELEN J.A. (1979) The pyroxene-plagioclase
achondrites. Smithsonian Contrib. Earth Sci. 22, 27-45.
- MAZOR E. and ANDERS E. (1967) Primordial gases in the Jodzie howardite and
the origin of gas-rich meteorites. Geochim. Cosmochim. Acta 31,
1441-1456.
- MERRILL G.P. (1920) Notes on the meteorite of Estherville, Iowa, with
especial reference to its included "peckhamite" and probable meta-
morphic nature. Proc. U.S. Nat. Mus. 58, 363-370.
- MERRILL G.P. (1925) Report on researches on the chemical and mineralogical
compositions of meteorites, with especial reference to their minor
constituents. Mem. Nat. Acad. Sci. 14, Mem. 1, 1-29, Mem 4, 1-15.
- MITTFEHLDT D.W. (1977) REE and igneous differentiation of the howardite
and mesosiderite parent bodies (abstr.). Meteoritics 12, 311-312.
- MITTFEHLDT D.W. (1978) Igneous fractionations on the howardite and meso-
siderite parent bodies (abstr.). Meteoritics 13, 566-567.
- MITTFEHLDT D.W. (1979a) The nature of asteroidal differentiation processes:
implications for primordial heat sources. Proc. Lunar Planet. Sci.
Conf. 10th, pp. 1975-1993. Pergamon.
- MITTFEHLDT D.W. (1979b) Petrographic and chemical characterization of
igneous lithic clasts from mesosiderites and howardites and comparison
with eucrites and diogenites. Geochim. Cosmochim. Acta 43, 1917-1935.
- MITTFEHLDT D.W., CHOU C.-L., and WASSON J.T. (1979) Mesosiderites and
howardites: igneous formation and possible genetic relationships.

- Geochim. Cosmochim. Acta **43**, 673-688.
- MIYAMOTO M. and TAKEDA H. (1977) Evaluation of a crust model of eucrites from the width of exsolved pyroxene. Geochem. J. **11**, 161-169.
- MIYAMOTO M., TAKEDA H., and YANAI K. (1978) Yamato achondrite polymict breccias. Mem. Nat. Inst. Polar Res., Spec. Issue **8**, 185-197.
- MIYAMOTO M., TAKEDA H., YANAI K., and HARAMURA H. (1979) Mineralogical examination of the Allan Hills No. 5 meteorite. Mem. Nat. Inst. Polar Res., Spec. Issue **12**, 59-71.
- MOORE C.B. (1962) The petrochemistry of the achondrites. In Researches on Meteorites, (editor C.B. Moore), pp. 164-178. John Wiley.
- MORELAND G.C., INGRAM F., and BANKS H.H. (1972) Preparation of doubly-polished thin sections. Smithsonian Contrib. Earth Sci. **9**, 93-94.
- MORGAN J.W. and LOVERING J.F. (1973) Uranium and thorium in achondrites. Geochim. Cosmochim. Acta **37**, 1697-1707.
- MORGAN J.W., HIGUCHI H., TAKAHASHI H., and HERTOGEN J. (1978) A "chondritic" eucrite parent body: inference from trace elements. Geochim. Cosmochim. Acta **42**, 27-38.
- MÜLLER O. and ZÄHRINGER J. (1966) Chemische Unterschiede bei uredelgas-haltigen Steinmeteoriten. Earth Planet. Sci. Lett. **1**, 25-29.
- MURTHY V.R., COSCIO M.R., and SABELIN T. (1977) Rb-Sr internal isochron and the initial $^{87}\text{Sr}/^{86}\text{Sr}$ for the Estherville mesosiderite. Proc. Lunar Sci. Conf. 8th, pp. 177-186. Pergamon.
- NAGASAWA H., SCHREIBER H.D., and BLANCHARD D.P. (1976) Partition coefficients of REE and Sc in perovskite, melilite, and spinel and their implications for Allende inclusions (abstr.). In Lunar Science VII, pp. 588-590. The Lunar Science Institute, Houston.
- NAKAMURA N., UNRUH D.M., GENSHO R., and TATSUMOTO M. (1977) Evolution history of lunar mare basalts: Apollo 15 samples revisited (abstr.). In

- Lunar Science VIII, pp. 712-713. The Lunar Science Institute, Houston.
- NEHRU C.E., HARLOW G.E., PRINZ M., and HEWINS R.H. (1978) The tridymite-phosphate-rich component in mesosiderites (abstr.). Meteoritics 13, 573.
- NELEN J.A. and MASON B. (1972) The Estherville meteorite. Smithsonian Contrib. Earth Sci. 9, 55-56.
- NOONAN A.F. (1974) Glass particles and shock features in the Bununu howardite. Meteoritics 9, 233-242.
- NOONAN A.F., RAJAN R.S., and CHODOS A.A. (1974) Microprobe analyses of glassy particles from howardites (abstr.). Meteoritics 9, 385-386.
- NORRISH K. and CHAPPELL B.W. (1967) X-ray fluorescence spectrography. In Physical Methods in Determinative Mineralogy, (editor J. Zussman), pp. 161-214. Academic Press.
- NORRISH K. and HUTTON J.T. (1969) An accurate X-ray spectrographic method for the analysis of a wide range of geological samples. Geochim. Cosmochim. Acta 33, 431-453.
- OKADA A. (1975) Petrological studies of the Yamato meteorites. Part 1. Mineralogy of the Yamato meteorites. Mem. Nat. Inst. Polar Res., Spec. Issue 5, 14-66.
- OKADA A., YAGI K., and SHIMA M. (1975) Petrological studies of the Yamato meteorites. Part 2. Petrology of the Yamato meteorites. Mem. Nat. Inst. Polar Res., Spec. Issue 5, 67-82.
- OLSEN E.J., NOONAN A., FREDRIKSSON K., JAROSEWICH E., and MORELAND G. (1978) Eleven new meteorites from Antarctica, 1976-1977. Meteoritics 13, 209-225.
- ONUMA N., HIGUCHI H., WAKITA H., and NAGASAWA H. (1968) Trace element partition between two pyroxenes and the host lava. Earth Planet. Sci.

Lett. 5, 47-51.

PALME H., BADDENHAUSEN H., BLUM K., CENDALES M., DREIBUS G., HOFMEISTER H., KRUSE H., PALME C., SPETTEL B., VILCSEK E., WÄNKE H., and KURAT G. (1978) New data on lunar samples and achondrites and a comparison of the least fractionated samples from the Earth, the Moon, and the eucrite parent body. Proc. Lunar Planet. Sci. Conf. 9th, pp. 25-57. Pergamon.

PAPANASTASSIOU D.A. and WASSERBURG G.J. (1969) Initial strontium isotopic abundances and the resolution of small time differences in the formation of planetary objects. Earth Planet Sci. Lett. 5, 361-376.

PATTERSON C.C. (1955) The Pb^{207}/Pb^{206} ages of some stone meteorites. Geochim. Cosmochim. Acta 7, 151-153.

PATTERSON C.C. (1956) Age of meteorites and the Earth. Geochim. Cosmochim. Acta 10, 230-237.

PHILPOTTS J.A. and SCHNETZLER C.C. (1970) Apollo 11 lunar samples: K, Rb, Sr, Ba, and rare-earth concentrations in some rocks and separated phases. Proc. Apollo 11 Lunar Sci. Conf., pp. 1471-1486. Pergamon.

PHILPOTTS J.A., SCHNETZLER C.C., and THOMAS H.H. (1967) Rare-earth and barium abundances in the Bununu howardite. Earth Planet. Sci. Lett. 2, 19-22.

PINSON W.H., SCHNETZLER C.C., BEISER E., FAIRBAIRN H.W., and HURLEY P.M. (1965) Rb-Sr age of stony meteorites. Geochim. Cosmochim. Acta 29, 455-466.

POWELL B.N. (1969a) Petrology and chemistry of mesosiderites. Ph.D. thesis, Columbia University. 188 pp.

POWELL B.N. (1969b) Petrology and chemistry of mesosiderites - I. Textures and composition of nickel-iron. Geochim. Cosmochim. Acta 33, 789-810.

POWELL B.N. (1971) Petrology and chemistry of mesosiderites - II. Silicate

textures and compositions, and metal-silicate relationships.

Geochim. Cosmochim. Acta 35, 5-34.

PRESNALL D.C. (1969) The geometrical analysis of partial fusion. Amer. J. Sci. 267, 1178-1194.

PRINZ M., FODOR R.V., and KEIL K. (1977) Comparison of lunar rocks and meteorites: implications to histories of the Moon and parent meteorite bodies. Soviet-American Conf. Cosmochem. Moon and Planets (NASA SP-370), Vol. 1, pp. 183-199.

PRINZ M., NEHRU C.E., BERKLEY J.L., KEIL K., JAROSEWICH E., and GOMES C.B. (1977) Petrogenesis of the Serra de Magé cumulate eucrite (abstr.). Meteoritics 12, 341.

PRINZ M., NEHRU C.E., DELANEY J.S., HARLOW G.E., and BEDELL R.L. (1980) Modal studies of mesosiderites and related achondrites, including the new mesosiderite ALHA 77219. Proc. Lunar Planet. Sci. Conf. 11th, pp. 1055-1071. Pergamon.

PRIOR G.T. (1910) On a meteoric stone from Simondium, Cape Colony. Mineral. Mag. 15, 312-314.

PRIOR G.T. (1918) On the mesosiderite-grahamite group of meteorites: with analyses of Vaca Muerta, Hainholz, Simondium, and Powder Mill Creek. Mineral. Mag. 18, 151-172.

PRIOR G.T. (1920) The classification of meteorites. Mineral. Mag. 19, 51-63.

PRIOR G.T. (1921) On the South African meteorites Mount Ayliff and Simondium, and the chemical composition of the meteorites Adare and Ensishheim. Mineral. Mag. 19, 163-172.

RAJAN R.S., BROWNLEE D.E., HEIKEN G.H., and McKAY D.S. (1974) Glassy agglutinate-like objects in the Bununu howardite (abstr.). Meteoritics 9, 394-396.

RAJAN R.S., HUNEKE J.C., SMITH S.P., and WASSERBURG G.J. (1975) ^{40}Ar - ^{39}Ar

- chronology of isolated phases from Bununu and Malvern howardites.
Earth Planet. Sci. Lett. 27, 181-190.
- RAJAN R.S., HUNEKE J.C., SMITH S.P., and WASSERBURG G.J. (1979) Argon 40-argon 39 chronology of lithic clasts from the Kapoeta howardite.
Geochim. Cosmochim. Acta 43, 957-971.
- RAMDOHR P. (1963) The opaque minerals in stony meteorites. J. Geophys. Res. 68, 2011-2036.
- RAMDOHR P. (1966) Observations on the opaque ore content of some meteorites, especially from New South Wales. J. Proc. Roy. Soc. New South Wales 99, 45-55.
- RAMDOHR P. (1973) The Opaque Minerals in Stony Meteorites. 245 pp.
Elsevier.
- REED S.J.B. (1964) Composition of the metallic phase in some stone and stony-iron meteorites. Nature 204, 374-375.
- REID A.M. (1974) The Macibini meteorite and some thoughts on the origin of basaltic achondrites (abstr.). Meteoritics 9, 398-399.
- REID A.M. (1982) Overview of Antarctic achondrites. In Catalog of Meteorites from Victoria Land, Antarctica, 1978-1980, (editors U.B. Marvin and B. Mason), pp. 59-64. (Smithsonian Contrib. Earth Sci. 24).
- REID A.M. and BARNARD B.M. (1979) Unequilibrated and equilibrated eucrites (abstr.). In Lunar and Planetary Science X, pp. 1019-1021. The Lunar Institute, Houston.
- REID A.M. and DUKE M.B. (1981) The basaltic meteorites. In Basaltic Volcanism on the Terrestrial Planets, pp. 214-235. Pergamon.
- REID A.M. and LOVERING J.F. (1969) Phase compositions in achondrites (abstr.). Trans. Amer. Geophys. Union 50, 223.
- REID A.M., BARNARD B.M., SIMPSON A.B., MCGRAW M., SCHULTZ R., and REID K. (1977) A bibliography of achondritic and related meteorites.

(Privately distributed microfiche).

- REID A.M., DUNCAN A.R., and LE ROEX A.P. (1979) Petrogenetic models for eucrite genesis (abstr.). In Lunar and Planetary Science X, pp. 1022-1024. The Lunar Science Institute, Houston.
- REID A.M., MEYER C., HARMON R.S., and BRETT R. (1970) Metal grains in Apollo 12 igneous rocks. Earth Planet. Sci. Lett. 9, 1-5.
- REID D.L. (1977) Geochemistry of Precambrian igneous rocks in the lower Orange River region. Ph.D. thesis, University of Cape Town. 397 pp.
- REYNOLDS R.C. (1963) Matrix corrections in trace element analysis by X-ray fluorescence. Estimation of the mass absorption coefficient by Compton scattering. Amer. Mineral. 48, 1133-1143.
- RINGWOOD A.E. (1961) Chemical and genetic relationships among meteorites. Geochim. Cosmochim. Acta 24, 159-197.
- ROEDER P.L. and EMSLIE R.F. (1970) Olivine-liquid equilibrium. Contrib. Mineral. Petrol. 29, 275-289.
- RUCKLIDGE J.C. (1976) Electron microprobe instrumentation. In Microbeam Techniques: Short Course Handbook, (editor D.G.W. Smith), pp. 1-44. Mineralogical Association of Canada.
- SCHAAL R.B., HÖRZ F., and GIBBONS R.V. (1976) Shock metamorphic effects in lunar microcraters. Proc. Lunar Sci. Conf. 7th, pp. 1039-1054. Pergamon.
- SCHMITT R.A. and LAUL J.C. (1973) A survey of the selenochemistry of major, minor, and trace elements. The Moon 8, 182-209.
- SCHMITT R.A., BINGHAM E., and CHODOS A.A. (1964a) Zirconium abundances in meteorites and implications to nucleosynthesis. Geochim. Cosmochim. Acta 28, 1961-1979.
- SCHMITT R.A., GOLES G.G., SMITH R.H., and OSBORN T.W. (1972) Elemental abundances in stone meteorites. Meteoritics 7, 131-214.

SCHMITT R.A., SMITH R.H., and OLEHY D.A. (1964b) Rare-earth, yttrium and scandium abundances in meteoritic and terrestrial matter - II. Geochim. Cosmochim. Acta 28, 67-86.

SCHMITT R.A., SMITH R.H., LASCH J.E., MOSEN A.W., OLEHY D.A., and VASILEVSKIS J. (1963) Abundances of the fourteen rare-earth elements, scandium, and yttrium in meteoritic and terrestrial matter. Geochim. Cosmochim. Acta 27, 577-622.

SCHNETZLER C.C. and PHILPOTTS J.A. (1969) Genesis of the calcium-rich achondrites in light of rare-earth and barium concentrations. In Meteorite Research, (editor P.M. Millman), pp. 206-216. D. Reidel Publ. Co.

SCORE R., KING T.V.V., SCHWARZ C.M., REID A.M., and MASON B. (1982) Descriptions of stony meteorites. In Catalog of Meteorites from Victoria Land, Antarctica, 1978-1980, (editors U.B. Marvin and B. Mason), pp. 19-48. (Smithsonian Contrib. Earth Sci. 24).

SHIMA M. (1974) The chemical composition of the stone meteorites, Yamato (a), (b), (c) and (d), and Numakai. Meteoritics 9, 123-135.

SHIMIZU N. and ALLÈGRE C.J. (1975) The genetic relationships among diogenites, howardites, and eucrites (abstr.). Meteoritics 10, 488.

SIMONDS C.H. (1973) Sintering and hot pressing of Fra Mauro composition glass and the lithification of lunar breccias. Amer. J. Sci. 273, 428-439.

SIMPSON A.B. (1974) Electron microprobe investigation of the achondritic meteorite Malvern (abstr.). Proc. Electron Microsc. Soc. S. Afr. 4, 77-78.

SIMPSON A.B. (1975) Electron microprobe investigation of the howardite Malvern (abstr.). Meteoritics 10, 489-491.

SIMPSON A.B. and AHRENS L.H. (1977) The chemical relationship between howardites and the silicate fraction of mesosiderites. In Comets,

- Asteroids, Meteorites - Interrelations, Evolution and Origins,
(editor A.H. Delsemme), pp. 445-450. University of Toledo Press.
- SIMPSON A.B. and AHRENS L.H. (1979) The Mg-Cr relationship in achondrites and in the silicate fraction of mesosiderites, and additional observations on eucrites. Meteoritics 14, 215-232.
- STOLPER E.M. (1975a) Experimental petrology of the Juvinas eucrite (abstr.). Meteoritics 10, 498-499.
- STOLPER E.M. (1975b) Petrogenesis of eucrite, howardite and diogenite meteorites. Nature 258, 220-222.
- STOLPER E.M. (1977a) Experimental petrology of eucritic meteorites. Geochim. Cosmochim. Acta 41, 587-611.
- STOLPER E.M. (1977b) Origins of cumulate eucrites (abstr.). Meteoritics 12, 366-367.
- STOLPER E.M., HAYS J.F., and MCSWEEN H.Y. (1978) A petrogenetic model relating the basaltic achondrites, the shergottites, the nakhlites, and the chassignites (abstr.). Meteoritics 13, 640-641.
- STOLPER E.M., MCSWEEN H.Y., and HAYS J.F. (1979) A petrogenetic model of the relationships among achondritic meteorites. Geochim. Cosmochim. Acta 43, 589-602.
- STRECKEISEN A.L. (1973) Plutonic rocks: classification and nomenclature recommended by the IUGS Subcommittee on the Systematics of Igneous Rocks. Geotimes 18, (10), 26-30.
- SUESS H.E., WÄNKE H., and WLOTZKA F. (1964) On the origin of gas-rich meteorites. Geochim. Cosmochim. Acta 28, 595-607.
- SUNG C.-M., ABU-EID R.M., and BURNS R.G. (1974) Ti^{3+}/Ti^{4+} ratios in lunar pyroxenes: implications to depth of origin of mare basalt magma. Proc. Lunar Sci. Conf. 5th, pp. 717-726. Pergamon.
- SWEATMAN T.R. and LONG J.V.P. (1969) Quantitative electron-probe microanalysis

- of rock-forming minerals. J. Petrol. 10, 332-379.
- TAKEDA H. (1979) A layered-crust model of a howardite parent body. Icarus 40, 455-470.
- TAKEDA H. and ISHII T. (1975) Pyroxene geothermometry applied to lunar crustal rocks and meteorites (abstr.). Meteoritics 10, 499-500.
- TAKEDA H. and MIYAMOTO M. (1977) Inverted pigeonites from lunar breccia 76255 and pyroxene crystallization trends in lunar and achondritic crusts. Proc. Lunar Sci. Conf. 8th, pp. 2617-2626. Pergamon.
- TAKEDA H. and REID A.M. (1972) Crystallography and chemical trends of pigeonites in some basaltic achondrites (abstr.). EOS 53, 437.
- TAKEDA H., MIYAMOTO M., and ISHII T. (1980) Comparison of basaltic clasts in lunar and eucritic polymict breccias. Proc. Lunar Planet. Sci. Conf. 11th, pp. 135-147. Pergamon.
- TAKEDA H., MIYAMOTO M., DUKE M.B., and ISHII T. (1978a) Crystallization of pyroxenes in lunar KREEP basalt 15386 and meteoritic basalts. Proc. Lunar Planet. Sci. Conf. 9th, pp. 1157-1171. Pergamon.
- TAKEDA H., MIYAMOTO M., YANAI K., and HARAMURA H. (1978b) A preliminary mineralogical examination of the Yamato-74 achondrites. Mem. Nat. Inst. Polar Res., Spec. Issue 8, 170-184.
- TAKEDA H., MIYAMOTO M., and ISHII T. (1979a) Pyroxenes in early crustal cumulates found in achondrites and lunar highland rocks. Proc. Lunar Planet. Sci. Conf. 10th, pp. 1095-1107. Pergamon.
- TAKEDA H., MIYAMOTO M., ISHII T., YANAI K., and MATSUMOTO Y. (1979b) Mineralogical examination of the Yamato-75 achondrites and their layered crust model. Mem. Nat. Inst. Polar Res., Spec. Issue 12, 82-108.
- TAKEDA H., MIYAMOTO M., ISHII T., and REID A.M. (1976) Characterization of crust formation on a parent body of achondrites and the Moon by

- pyroxene crystallography and chemistry. Proc. Lunar Sci. Conf. 7th, pp. 3535-3548. Pergamon.
- TAKEDA H., REID A.M., and YAMANAKA T. (1975) Crystallographic and chemical studies of a bronzite and chromite in the Yamato (b) achondrite. Mem. Nat. Inst. Polar Res., Spec. Issue 5, 83-90.
- TATSUMOTO M., KNIGHT R.J., and ALLEGRE C.J. (1973) Time differences in the formation of meteorites as determined from the ratio of lead-207 to lead-206. Science 180, 1279-1283.
- TAYLOR H.P. and EPSTEIN S. (1970) O^{18}/O^{16} ratios of Apollo 11 lunar rocks and minerals. Proc. Apollo 11 Lunar Sci. Conf., pp. 1613-1626. Pergamon.
- TAYLOR H.P., DUKE M.B., SILVER L.T., and EPSTEIN S. (1965) Oxygen isotope studies of minerals in stony meteorites. Geochim. Cosmochim. Acta 29, 489-512.
- TAYLOR S.R. (1975) Lunar Science: A Post-Apollo View. 372 pp. Pergamon.
- TERA F., EUGSTER O., BURNETT D.S., and WASSERBURG G.J. (1970) Comparative study of Li, Na, K, Rb, Cs, Ca, Sr and Ba abundances in achondrites and in Apollo 11 lunar samples. Proc. Apollo 11 Lunar Sci. Conf., pp. 1637-1657. Pergamon.
- UNRUH D.M., NAKAMURA N., and TATSUMOTO M. (1977) History of the Pasamonte achondrite: relative susceptibility of the Sm-Nd, Rb-Sr, and U-Pb systems to metamorphic events. Earth Planet. Sci. Lett. 37, 1-12.
- UREY H.C. (1959) Primary and secondary objects. J. Geophys. Res. 64, 1721-1737.
- UREY H.C. and CRAIG H. (1953) The composition of stone meteorites and the origin of meteorites. Geochim. Cosmochim. Acta 4, 36-82.
- VON ENGELHARDT W. (1963) Der Eukrit von Stannern. Beitr. Mineral. Petrol. 9, 65-94.

- VON MICHAELIS H. (1969) Fractionation of lithophile elements in chondritic meteorites. Ph.D. thesis, University of Cape Town. 175 pp.
- VON MICHAELIS H., AHRENS L.H., and WILLIS J.P. (1969) The composition of stony meteorites (II). The analytical data and an assessment of their quality. Earth Planet. Sci. Lett. 5, 387-394.
- WAGER L.R., BROWN G.M., and WADSWORTH W.J. (1960) Types of igneous cumulates. J. Petrol. 1, 73-85.
- WAHL W. (1952) The brecciated stony meteorites and meteorites containing foreign fragments. Geochim. Cosmochim. Acta 2, 91-117.
- WALKER D., LONGHI J., and HAYS J.F. (1972) Experimental petrology and origin of Fra Mauro rocks and soil. Proc. Lunar Sci. Conf. 3rd, pp. 797-817. M.I.T. Press.
- WALKER D., POWELL M.A., LOFGREN G.E., and HAYS J.F. (1978) Dynamic crystallization of a eucrite basalt. Proc. Lunar Planet. Sci. Conf. 9th, pp. 1369-1391. Pergamon.
- WÄNKE H., BADDENHAUSEN H., DREIBUS G., JAGOUTZ E., KRUSE H., PALME H., SPETTEL B., and TESCHKE F. (1973) Multielement analyses of Apollo 15, 16 and 17 samples and the bulk composition of the Moon. Proc. Lunar Sci. Conf. 4th, pp. 1461-1481. Pergamon.
- WARNER J.L. (1972) Metamorphism of Apollo 14 breccias. Proc. Lunar Sci. Conf. 3rd, pp. 623-643. M.I.T. Press.
- WASSON J.T. (1974) Meteorites: Classification and Properties. 316 pp. Springer-Verlag.
- WASSON J.T. and BAEDCKER P.A. (1970) Ga, Ge, In, Ir and Au in lunar, terrestrial and meteoritic basalts. Proc. Apollo 11 Lunar Sci. Conf., pp. 1741-1750. Pergamon.
- WASSON J.T., SCHAUDY R., BILD R.W., and CHOU C.-L. (1974) Mesosiderites. 1. Compositions of their metallic portions and possible relationship to

- other metal-rich meteorite groups. Geochim. Cosmochim. Acta 38, 135-149.
- WEIGAND P.W. (1975) Pyroxenes in the Patwar mesosiderite. Meteoritics 10, 341-351.
- WEILL D.F., McCALLUM I.S., BOTTINGA Y., DRAKE M.J., and MCKAY G.A. (1970) Mineralogy and petrology of some Apollo 11 igneous rocks. Proc. Apollo 11 Lunar Sci. Conf., pp. 937-955. Pergamon.
- WETHERILL G.W. (1976) Where do the meteorites come from? A re-evaluation of the Earth-crossing Apollo objects as sources of chondritic meteorites. Geochim. Cosmochim. Acta 40, 1297-1317.
- WIIK H.B. (1969) On regular discontinuities in the composition of meteorites. Soc. Sci. Fennica, Comm. Phys.-Math. 34, 135-145.
- WILKENING L.L. (1971) Particle track studies and the origin of gas-rich meteorites. Center for Meteorite Studies, Arizona State University, Publ. 11. 36 pp.
- WILKENING L.L. (1973) Foreign inclusions in stony meteorites - I. Carbonaceous chondritic xenoliths in the Kapoeta howardite. Geochim. Cosmochim. Acta 37, 1985-1989.
- WILKENING L.L. (1977) Meteorites in meteorites: evidence for mixing among the asteroids. In Comets, Asteroids, Meteorites - Interrelations, Evolution and Origins, (editor A.H. Delsemme), pp. 389-395. University of Toledo Press.
- WILKENING L.L., LAL D., and REID A.M. (1971) The evolution of the Kapoeta howardite based on fossil track studies. Earth Planet. Sci. Lett. 10, 334-340.
- WILLIAMS R.J. (1972) The lithification and metamorphism of lunar breccias. Earth Planet. Sci. Lett. 16, 250-256.
- WILLIS J.P. (1978) Some aspects of the geochemistry of gallium in silicate

rocks and stony meteorites. Ph.D. thesis, University of Cape Town.
741 pp.

WILLIS J.P., AHRENS L.H., DANCHIN R.V., ERLANK A.J., GURNEY J.J., HOFMEYR
P.K., MCCARTHY T.S., and ORREN M.J. (1971) Some interelement relation-
ships between lunar rocks and fines, and stony meteorites. Proc.
Lunar Sci. Conf. 2nd, pp. 1123-1138. M.I.T. Press.

WILLIS J.P., ERLANK A.J., GURNEY J.J., THEIL R.H., and AHRENS L.H. (1972)
Major, minor, and trace element data for some Apollo 11, 12, 14, and
15 samples. Proc. Lunar Sci. Conf. 3rd, pp. 1269-1273. M.I.T. Press.

WILLIS J.P., FESQ H.W., KABLE E.J.D., and BERG G.W. (1969) The determination
of barium in rocks by X-ray fluorescence spectrometry. Can.
Spectrosc. 14, 3-11.

WLOTZKA F., JAGOUTZ E., SPETTEL B., BADDENHAUSEN H., BALACESCU A., and
WÄNKE H. (1972) On lunar metallic particles and their contribution to
the trace element content of Apollo 14 and 15 soils. Proc. Lunar Sci.
Conf. 3rd, pp. 1077-1084. M.I.T. Press.

YAGI K., LOVERING J.F., SHIMA M., and OKADA A. (1978) Petrology of the
Yamato meteorites (j), (k), (l) and (m) from Antarctica. Meteoritics
13, 23-45.

APPENDIX 1

DIRECTORY OF SAMPLE NAMES

As indicated in the Introduction, a large number of electron microprobe analyses were carried out on mineral and lithic phases in the achondrites Binda, Bununu, Frankfort, Malvern, and Molteno. To provide a guide to these analyses, a directory of the complete sample names assigned to the individual phases analyzed was compiled and is appended as a microfiche listing subdivided into Tables A1.1-A1.41. The compilation was accomplished by suitable editing of the 41 computer file elements in which the original microprobe analyses (see Appendix 2) were stored. The editing was carried out on a terminal of the University's Sperry Univac 1108 computer, using the CTS (Conversational Time Sharing) processor.

The directory thus produced contains only the card images with laboratory names and supplementary observations made at the time of analysis. It has received no 'polishing' other than the standardization of the naming system and of the format of presentation of additional information, where applicable. An explanation of the standard naming system adopted follows: The general form of a name may be represented by:

MMP(PP)X/YY - additional information or (additional information)*

where

MM = a two-letter code identifying the meteorite in which the analyzed phase occurs, as follows:

BI - Binda

BU - Bununu

FR - Frankfort

MA - Malvern

MO - Molteno

* Where 'additional information' is enclosed within parentheses, it indicates that more than one analysis was performed on that mineral or lithic phase.

P(PP) = a code consisting of 1-3 letters that characterizes the phase analyzed, as follows:

CR - chromite	IL - ilmenite	M - metal
OL - olivine	PL - plagioclase	PX - pyroxene
PG - pigeonite	OP - orthopyroxene	SI - silica mineral
TR - troilite	GF - glass	MBR - glassy microbreccia

Less commonly may be found:

AU - augite	LP - lamellar pyroxene

X/ = a single digit indicating the number of the polished thin section in which the phase occurs (omitted when only one section was available for study)

YY = a two-digit number identifying the individual phase analyzed

Note: the apparent discrepancy that exists between this numbering system (maximum of 99) and Table 1.2, in which it is recorded that 105 and 107 pyroxenes were analyzed in single sections of Bununu and Frankfort respectively, is accounted for by host and lamellar phases that fall under a single sample name.

Example:

The sample designation 'MOPL4/06 - IN C-G LITHIC CLAST WITH MOPX4/20' refers to the sixth plagioclase analyzed in the fourth section of Molteno that was studied, and indicates that only one analysis was carried out on that crystal.

APPENDIX 2

MICROPROBE ANALYSES OF THE CONSTITUENT PHASES OF THE ACHONDRITES STUDIED: THE ORIGINAL DATA

After reduction as described in Appendix 8, the corrected microprobe analyses of representatives of the phases present in the five achondrites investigated were used as input to a version of the departmental computer program PROBELIST. This program was modified by the writer to accept these analytical data and to output, in the desired format, the results of the processing performed. PROBELIST lists and sums analyses expressed in terms of oxide concentrations, and recalculates these analyses to atomic proportions on the basis of the number of oxygens specified (see Appendix 1, DEER et al., 1966). This recalculation is carried out for each analysis presented, but is meaningful only for O-bearing minerals. Analyses of metals and troilites were listed by programs adapted for the purpose by the writer. These programs, designated LIST/FICHMET and LIST/TROIL respectively, dispense with the unnecessary recalculation procedure. All three programs present 10 analyses per page of computer print-out, together with the appropriate recalculations (if performed) and identifying particulars - frequently truncated but available in full in Appendix 1 - of the samples analyzed. The original analytical data from the microprobe investigation are presented in full in this Appendix in the form of computer output page images reproduced on microfiche. The data are subdivided into Tables A2.1-A2.41 according to meteorite and phase, and an index to the locations of these subdivisions on the microfiche cards may be found in the usual position on each card.

PROBELIST also calculates the 'molecular' percentages of binary or ternary components present in each mineral analysis. The components for olivine, plagioclase, and pyroxene are familiar and need no explanation, but

caution must be exercised over chromite and ilmenite. The program automatically calculates Fe_2O_3 for chromite and ilmenite. If, as in the present investigation, the samples are in a reduced condition and Fe can be assumed to occur as FeO, this recalculation is meaningless and does not appear in the representative analyses of chromites and ilmenites in the text (Tables 6.1 and 6.2). In addition, the recalculated percentages of 'Cr', 'Mg', and 'Fe', which represent the ratios $\text{Cr}/\text{Cr}+\text{Al}$, $\text{Mg}/\text{Mg}+\text{Fe}^{2+}$, and $\text{Fe}^{3+}/\text{Cr}+\text{Al}+\text{Fe}^{3+}$ in the chromites, and the percentages of ilmenite, geikielite, and haematite in the ilmenites, should be disregarded. These remarks apply equally to the averaged analyses of chromites and ilmenites listed in Appendix 3.

Further computational problems are evident in the presentation of the analyses of a few glasses in Molteno that contain appreciable amounts of S, for which no provision was made in the program. These analyses, which appear in Table A2.35 (and Table A3.35), accordingly show low totals, but the full analyses and correct summations may be found in the norm calculations of Appendix 5 (Table A5.3). It was not considered worthwhile modifying PROBELIST because of this very specialized problem that involved only a few analyses.

APPENDIX 3

MICROPROBE ANALYSES OF THE CONSTITUENT PHASES
OF THE ACHONDRITES STUDIED: THE AVERAGED DATA

The original microprobe data presented in Appendix 2 contain many examples of multiple analyses carried out on individual minerals or lithic clasts so that a more reliable estimate of their bulk composition could be obtained by averaging these analyses. The onerous task of averaging the data was performed by a computer program designated METMEAN, devised by the writer. The averaged data are presented on microfiche in this appendix in a manner similar to that used for the original data (Appendix 2). The single analyses also are included in this presentation, because all calculations, plotting, and statistical analyses are based on the data contained in this appendix. In this tabulation of analyses, the single analyses retain their original titles, i.e. those that appear in Appendices 1 and 2, whereas the averaged analyses have been re-titled to indicate that they are averages. A number in brackets in the new title indicates how many analyses have been used to calculate the average. Prior to averaging, the original data were examined carefully for outlying values that are obviously erroneous. Such values, which form only a very small proportion of the data, were excluded from the averages.

Attention is drawn to the remarks in Appendix 2 on the computer recalculation of analyses of chromites and ilmenites, and on the listing of S-bearing glasses in Molteno. It should be appreciated that the minor deficiencies specified in these remarks apply to the presentation of the data only, and do not affect the use of the data in operations such as plotting of inter-element relationships.

APPENDIX 4

CIPW NORMS CALCULATED FROM ANALYSES OF ACHONDRITES
AND THE SILICATE FRACTIONS OF MESOSIDERITES

CIPW norms were calculated from the XRF analyses of achondrites and mesosiderites that were performed as part of the present investigation. In addition, norms were obtained for selected published analyses of achondrites and mesosiderites, mainly for purposes of comparison with the normative compositions calculated from the microprobe analyses of glassy and fine-grained constituents of Binda, Bununu, Frankfort, Malvern, and Molteno (Appendix 5). The departmental computer program NEWNORM, which was adapted by D.L. Reid from a program that originated in the University of California (Berkeley), was used to carry out the calculations. NEWNORM outputs one norm, together with various mineral and element ratios and other plotting information calculated by the program, per page of print-out. These page images are reproduced in this appendix on microfiche, and are indexed in the customary manner. There are six tables in the appendix, the order in which the meteorites appear being the same as that of their analyses in the text (Tables 4.2, 4.4, and 4.7-4.9).

APPENDIX 5

CIPW NORMS CALCULATED FROM MICROPROBE ANALYSES OF GLASSY AND FINE-GRAINED PHASES IN THE FIVE ACHONDRITES STUDIED

Calculation of CIPW norms for the microprobe analyses of glassy and fine-grained (i.e. devitrified glassy) materials offers a means of comparison of these phases with one another and with the bulk meteorites whose norms are listed in Appendix 4. The calculations were carried out on the relevant averaged data contained in Appendix 3, in this instance by a program called NEWNORM/PROBE. This is a version of NEWNORM, modified by the writer, from which the calculation procedures based on elements that are not routinely determined by microprobe analysis have been eliminated. NEWNORM/PROBE therefore accepts analyses with up to 13 elements instead of the maximum of 23 elements handled by the original program, but its output format is the same as that of NEWNORM. As in Appendix 4, the norms in this appendix are presented on microfiche.

The appendix is subdivided into nine tables. Reference to Table A5.3, which contains the norms for glasses in Molteno, shows that the calculation procedure does not work well for the few glasses with a high content of S. The errors introduced are noted in Table 6.10, in which two norms representative of these materials are presented.

APPENDIX 6

SAMPLE PREPARATION

A6.1 X-ray fluorescence analysis

The routine procedures followed in the preparation of samples for XRF analysis in the Department of Geochemistry are outlined in WILLIS et al. (1971). Because of the small size of the samples available for analysis, the complete powdered samples were used to obtain 'infinite' sample thickness for the determination of Rb, Sr, Y, Zr, and Nb prior to the preparation of 1g pressed-powder briquettes for trace element analysis (BAIRD, 1961) and to lithium tetraborate fusion for major element analysis by the method of NORRISH and HUTTON (1969).

Although the separated silicate fractions of the mesosiderites investigated were prepared in the normal way, the separation procedure adopted requires description. All but two of the mesosiderite samples were received in the form of fragments (Table 1.1). These fragments were crushed in a high-carbon steel percussion mortar by means of an eccentric pestle of the same material. Care was taken to use just enough force to disaggregate the sample without causing the silicate grains to become embedded in the metal masses, which were flattened and distorted. Trials showed that a 40-mesh nylon screen effectively separated the bulk of the metal from the remainder of the sample, with seemingly minimal admixture of silicate material with the coarse metal. A 120-mesh screen further purified the silicate fraction. Metal was removed from both of the dominantly silicate fractions by means of a powerful industrial hand-magnet with a rotatable pole piece. The cycle of gentle crushing, screening, and magnetic separation was repeated until a fairly pure minus 120-mesh silicate fraction was obtained. This material was dispersed in A.R. acetone in a shallow Petri dish of 14 cm diameter, above which was suspended

the large magnet, its poles covered with transparent plastic sheeting. The magnet was lowered into the acetone until it was about 2 mm above the material strewn on the bottom of the vessel, and the sample was magnetically 'swept' by moving the dish around under the magnet. The gap between the magnet and the sample was adjusted for optimum results. The poles of the magnet were cleaned frequently, and the 'sweeping' process was continued until all the recoverable metal had been extracted from the sample.

Subsequent XRF analysis of the separated silicate fractions proved this simple separation technique to have been quite effective. Calculations based on the published Ni contents of the metals of the mesosiderites included in the present investigation (WASSON et al., 1974) indicated that only 1.1% (by weight) of metal remained in the Patwar silicates. The average metal impurity in the samples was 4.4%, the worst case being Mincy (6.5%).

A6.2 Electron microprobe analysis

Most of the sections used in the present study were borrowed (Binda, Bununu, and Frankfort) or were prepared overseas (Malvern). The doubly-polished thin sections of Molteno were, however, prepared in the Department of Geochemistry according to the method of MORELAND et al. (1972). All sections studied were rendered conductive by vacuum-coating with a thin film of carbon. Good electrical contact between the sections and the sample stage of the microprobe was effected by sparing use of a suspension of silver in collodion.

APPENDIX 7

X-RAY FLUORESCENCE ANALYSIS

A7.1 Instruments used

Most of the analytical work on bulk samples included in the present investigation was carried out on a Philips PW1220 2 kW semi-automatic spectrometer. Ba was determined on a Philips PW1540 1 kW manual spectrometer, as were mass absorption coefficients measured by the transmission method (NORRISH and CHAPPELL, 1967). A Siemens SRS 3 kW fully-automatic spectrometer was used to perform a few check determinations at the end of the analytical programme.

A7.2 Major elements

10 of the major elements analyzed in the achondrites, and 11 in the mesosiderites, were determined by the lithium tetraborate fusion method (NORRISH and HUTTON, 1969). The remaining two, Na and S, were determined using pressed-powder briquettes. These analyses, and the accompanying trace element determinations, were carried out at the same time, and under the same experimental conditions, as the analyses of lunar materials performed as part of the Department's programme of lunar research during the period 1973-1975.

The standardization was based on the U.S. Geological Survey rock standards G-1, W-1, BCR-1, GSP-1, AGV-1, PCC-1, and DTS-1, and on several local rock standards calibrated against them. The accuracy of the analyses is dependent on the confidence that can be placed on the accepted values for the element concentrations in these standards and cannot therefore be readily assessed other than by inspecting the analyses for satisfactory summations and by observing their response to plotting, recalculation, and statistical operations. The precision of the analyses, expressed as the average

Table A7.1. Estimates of the precision and detection limits of major element analyses of achondrite and mesosiderite samples by XRF

Oxide	ACHONDRITES			MESOSIDERITES			Detection limit (%)
	Average composition	Average s.d.	Average C. of V. (%)	Average composition	Average s.d.	Average C. of V. (%)	
SiO ₂	49.39	0.18	0.37	45.17	0.22	0.53	0.05
TiO ₂	0.418	0.004	0.84	0.269	0.003	1.10	0.007
Al ₂ O ₃	8.95	0.07	0.76	8.27	0.04	0.49	0.03
Cr ₂ O ₃	0.668	0.006	0.84	0.88	0.01	1.47	0.012
FeO*	17.87	0.05	0.27	20.30	0.12	0.53	0.02
MnO	0.522	0.006	0.98	0.478	0.005	1.06	0.007
MgO	14.03	0.10	0.71	14.02	0.09	0.68	0.12
NiO	---	---	---	0.419	0.004	0.91	0.003
CaO	7.14	0.03	0.42	6.41	0.03	0.50	0.01
Na ₂ O	0.27	0.01	5.96	0.25	0.004	1.24	0.08
K ₂ O	0.024	0.002	10.33	0.008	0.001	12.16	0.002
P ₂ O ₅	0.050	0.004	9.11	1.13	0.01	1.17	0.019
S	0.240	0.002	0.73	2.72	0.01	0.44	0.003

Notes: 1. s.d. - standard deviation
2. C. of V. - coefficient of variation

analytical standard deviation and the average coefficient of variation of each oxide, is presented in Table A7.1, together with the corresponding detection limits. These estimates of precision are similar to those given by WILLIS *et al.* (1972), DUNCAN *et al.* (1975), and REID (1977). Achondrites and mesosiderites were calculated separately because of the marked differences in the precision of some of the determinations between the two meteorite classes. In general, the precisions are of the order of 1% or less, except for some elements that occur in very low concentrations, e.g. the alkalis.

A7.3 Trace elements

Pressed-powder briquettes, or the complete samples in powder form, were used for the determination of 12 trace elements in the samples studied. However, Cr was found to occur in concentrations too high for reliable analysis by the pressed-powder method, and the values determined using Norrish fusion discs were adopted. This procedure was followed also for Ni in the mesosiderites. Nb, Zr, Y, Rb, and Sr were determined in the complete powdered sample by techniques modified from CHERRY et al. (1970) by WILLIS et al. (1971, 1972). The briquetted samples were analyzed for Ba by the method of WILLIS et al. (1969), and for the remaining trace elements as described by WILLIS et al. (1971). The mass absorption coefficients of the samples were originally determined by the method of REYNOLDS (1963) but, because some of the values obtained were suspected of being too low in spite of the complete sample having been used, all coefficients were re-determined by the transmission technique of NORRISH and CHAPPELL (1967), and the trace element analyses were adjusted accordingly.

Following the procedure adopted in the Department of Geochemistry to avoid systematic errors between different sets of data, the trace element analyses reported were standardized using G-1, W-1, BCR-1, and GSP-1, and a limited number of additional rocks calibrated against these standards. The accuracy of the analytical technique is indicated by the analyses of U.S. Geological Survey standards in Table 2 of WILLIS et al. (1972), which are in satisfactory agreement with values obtained by isotope dilution methods. Estimates of the analytical precision, determined in the same way as in the major element analyses, are given in Table A7.2. The average analytical standard deviations calculated are similar, for comparable concentrations, to those reported for analyses of Apollo 15 samples by DUNCAN et al. (1975). Table A7.2 also contains estimates of the lower limits of detection of the trace elements analyzed.

Table A7.2. Estimates of the precision and detection limits of trace element analyses of achondrite and mesosiderite samples by XRF

Element	ACHONDRITES				MESOSIDERITES			
	Ave. composition	Ave. s.d.	Ave. C. of V. (%)	D.L.	Ave. composition	Ave. s.d.	Ave. C. of V. (%)	D.L.
Rb	< 0.9	--	--	0.9	< 1.1	--	--	1.1
Ba	19	0.5	3.5	2.1	11	0.6	5.8	1.9
Sr	48	0.5	1.2	2.1	41	0.7	2.0	2.3
Zr	29	0.9	3.6	2.2	12	0.7	7.2	2.3
Nb	4	0.3	7.2	2.1	< 2.2	--	--	2.2
Y	11	0.5	4.9	1.9	8	0.7	7.7	2.1
(Cr)	4165	6	0.1	3.4	5048	40	0.8	3.3
V	95	1.4	1.4	4.6	95	1.3	1.5	4.3
Ni	224*	1.5	0.7	2.9	2882	4	0.1	2.6
Co	21*	1.5	7.5	5.8	103	1.8	3.0	5.4
Cu	17	0.5	3.9	2.3	29	0.5	6.3	2.0
Zn	14	0.3	2.4	1.5	4	0.3	11.2	1.3

- Notes:
1. All values in ppm unless otherwise stated
 2. s.d. - standard deviation
 3. C. of V. - coefficient of variation
 4. * Value excluding Binda, which is virtually metal-free
 5. D.L. - detection limit

APPENDIX 8

ELECTRON MICROPROBE ANALYSIS

A8.1 Instrumental details

All the micro-analyses included in the investigation were carried out using the Department's electron microprobe, a Cambridge Microscan 5 with two fully focussing wavelength-dispersive spectrometers. Samples were prepared as described in Appendix 6.

For the analysis of silicate materials, oxides, and sulphides, the instrument was operated at an accelerating potential of 15 kV and a probe current (as defined by RUCKLIDGE, 1976) of 150 nA, but for metals the settings were 25 kV and 50 nA. The standard 10-element analysis involved the use of two analyzing crystals - RAP (rubidium ammonium phthalate) for the lighter elements (Si, Al, Mg, and Na) and quartz for the remainder (Fe, Mn, Cr, Ca, Ti, and K) and, additionally, for S. A LiF_{200} crystal was used in the analysis of Ni and Co in metals and troilites, and the determination of P required a PET (penta-erythritol) crystal. Detection of the X-radiation emitted by the sample was normally by flow counters using Ar with a 2.5% content of damping agent (CO_2), but a sealed (Xe-filled) counter was used in the analyses of Ni and Co. Pulse height analysis was routinely employed to assist detector resolution and improve peak-to-background ratios of the analyzed elements. A permanent record of the outputs from the detectors (as opposed to transient displays such as scalers and cathode ray tubes) was provided by a high-speed printer.

A8.2 Analytical techniques

The majority of the analyses were performed with the electron beam defocused to diameters between 4 and 16 microns, tests having established

that count rates (and therefore standardization) remained unaffected by defocusing up to at least 30 microns. Defocusing was necessary in order to counteract small-scale inhomogeneities present in many of the materials analyzed, presumably as a result of shock. The distribution of Ca and Al in feldspars proved particularly inhomogeneous, and initially caused serious problems. Determination of the alkalis, especially in glassy matrices, also necessitated defocusing. Stability tests showed there to be no loss of Na and K, even at the high beam current used, provided that the defocusing was sufficient; a beam of 16 microns diameter was invariably used for glassy materials. A fully focused beam was, of course, required for the study of exsolution lamellae in pyroxenes because of their narrowness. Metals and troilites also were analyzed with a beam of about one micron diameter.

Counting times were 10 seconds for all elements except the alkalis, which were counted for 20 seconds. At least four measurements of peak counts and two of background were made for each element. Readings were taken on both sides of the characteristic peaks of Al, Mg, and Na because of the sloping background in that part of the X-ray spectrum.

Certain of the phases present, e.g. some plagioclases, orthopyroxenes, and olivines, proved sufficiently homogeneous to a beam defocused to about 8-12 microns that a single 'spot' analysis was adequate to establish the composition. In general, however, the composition of a crystal or glassy clast was obtained by averaging a number of analyses made at different points. This method was selected as the most reliable and reproducible way of determining bulk compositions. Bulk analyses made by mechanically translating the specimen stage so that the beam traversed the grain under investigation in a direction selected for freedom from inclusions, cracks, and other imperfections proved less reproducible and slower than the averaging technique. Consequently, this method of 'scanning' across the grain was abandoned after initial trials.

Because of the complex nature of the meteorite breccias studied, enlarged photomicrographs of the sections (40-50 times enlargement) were used in the performance of the analyses. Identifying names and numbers of the phases analyzed, and the locations of the analyses, were recorded on transparent overlays, in many instances together with supplementary petrographic information. This procedure additionally ensured that a reasonably random sampling of the various components was obtained.

A8.3 Standardization

The standards used to calibrate the electron microprobe were mainly natural minerals whose compositions had been established by other analytical techniques, but pure metals were used to standardize Fe in the metal phase, and Ni and Co in the metals and troilites. The complete standardization is summarized in Table A8.1.

A8.4 Reduction of the data

During the course of the investigation, two systems of computer reduction of the microprobe data were employed, one in succession to the other. Both correct the element counts for dead time and background and calculate nominal concentrations on the basis of the standard calibration established at the start of the analytical run. The earlier system made use of the program ABFAN (BOYD et al., 1968), input to which took the form of punched paper tape. With the introduction of a Varian 620-100 minicomputer, on-line reduction of the microprobe's output became possible using the alpha-factor method of BENCE and ALBEE (1968). This technique, however, is suitable only for silicates and oxides. The analyses of all metals and troilites included in this investigation, together with those of the S-rich glasses in Molteno, were therefore computed by the program T.I.M.1 (DUNCUMB and JONES, 1969).

Table A8.1. Standards employed in the electron microprobe analysis of mineral and lithic phases in this investigation

Chromite	Ilmenite	Metal	Olivine	Plagioclase	Pyroxene	Troilite	Glassy material
Si			M.O.	Di.	K.P.		K.P.
Ti	S.C.				K.P.		K.P.
Al	S.C.			K.P.	K.P.		K.H.
Cr	S.C.				S.C.		S.C.
V	S.C.						
Fe	S.C.	Fe metal	M.O.	K.P.	S.C.	SM-3	S.C.
Mn	S.C.				K.P.		K.P.
Mg	S.C.		M.O.		K.P.		K.H.
Ca			K.P.	Di.	K.P.		K.H.
Na				K.H.			K.H.
K				K.H.			K.H.
P							Ap.
Ni		Ni metal				Ni metal	
Co		Co metal				Co metal	
S						SM-3	

KEY: Ap. - apatite K.H. - Kakanui hornblende M.O. - Marjalahti olivine Di. - diopside
 K.P. - Kakanui pyrope Rut. - rutile S.C. - Stillwater chromite SM-3 - troilite SM-3

Use of the two main systems of data reduction could not be avoided because of the magnitude of the investigation and the resultant lengthy period during which microprobe analyses were performed. However, no systematic differences appear to have been introduced in the later analytical data by the empirical Bence-Albee technique.

A8.5 Precision and accuracy of the determinations

Because of the diversity of materials analyzed by electron microprobe in the course of this investigation, no estimation of the precision of the technique by repeated analysis of any one material was attempted. However, the work of SWEATMAN and LONG (1969) indicated that deviations from the mean of replicate microprobe analyses of major elements are of the same order of magnitude as the corresponding errors arising from statistical variations in the count rates. Confirmation of this conclusion is to be found in three widely differing investigations involving replicate analyses as a means of estimating the precision of microprobe techniques employed in this Department (REID, 1977; BIRCH, 1979; CARDOSO, 1980). Consequently, precision has been estimated in the present investigation by calculating variations in count rates at the 95 percent confidence level, and expressing them as percentages of the oxides analyzed. This procedure has been followed for two plagioclases (Table A8.2), an orthopyroxene and a pigeonite (Table A8.3), and two types of glassy material (Table A8.4), all of which are components of Malvern. The precision estimates have been expressed also as coefficients of variation. Except for oxides present in very low concentrations, these coefficients are generally below 1 percent, and in several instances they are less than 0.5 percent.

The accuracy of the analyses is less easy to assess. Internationally accepted standards, comparable to those used in macro-analysis, are not yet available for electron probe microanalysis. Some of the standards listed

Table A8.2. Estimates of the precision and detection limits of electron microprobe analyses of plagioclases

	MAPL1/16				MAPL4/04			
	Conc.	Err.	C.V.	D.L.	Conc.	Err.	C.V.	D.L.
SiO ₂	46.19	0.25	0.27	0.02	44.49	0.36	0.41	0.02
Al ₂ O ₃	34.48	0.21	0.30	0.02	34.92	0.31	0.45	0.02
FeO*	0.13	0.04	15.78	0.06	0.13	0.02	8.94	0.05
CaO	18.27	0.24	0.67	0.03	19.04	0.26	0.69	0.03
Na ₂ O	1.11	0.12	5.40	0.06	0.81	0.03	2.03	0.03
K ₂ O	0.05	0.02	15.14	0.02	0.02	0.01	16.03	0.02
TOTAL	100.23				99.41			

Notes (applicable also to Tables A8.3 and A8.4):

All values are expressed in weight percent of the oxide except C.V., which is dimensionless.

Err. - error present in the analysis (95 percent confidence limits) as a result of variation in counting statistics

C.V. - coefficient of variation

D.L. - theoretical limit of detection (99 percent confidence limits)

in Table A8.1 (e.g. the Kakanui suite of minerals, and Marjalahti olivine) have gained wide acceptance, but others used are of more limited recognition. Even in the case of the well-known standards, however, there is no certainty of homogeneity on a scale of microns. Nevertheless, certain criteria point to a reasonable degree of accuracy in the microprobe analyses. The vast majority of the summations of the analyses are satisfactory, and the recalculations of mineral analyses to atomic proportions are generally acceptable. More telling, however, is the consistency of behaviour of the analytical data in the various inter-element plots employed in this investigation. These data were amassed over a long period, but the standardization was kept constant throughout. Serious inaccuracies in the microprobe analyses would have obscured the trends and groupings that are consistently revealed in the

Table A8.3. Estimates of the precision and detection limits of electron microprobe analyses of pyroxenes

	MAOP2/12/1				MAPG2/15/1			
	Conc.	Err.	C.V.	D.L.	Conc.	Err.	C.V.	D.L.
SiO ₂	53.03	0.39	0.37	0.02	47.98	0.27	0.29	0.02
TiO ₂	0.13	0.06	22.52	0.03	0.31	0.05	7.58	0.04
Al ₂ O ₃	1.07	0.03	1.62	0.01	0.41	0.04	4.95	0.02
Cr ₂ O ₃	0.67	0.05	4.08	0.03	1.02	0.05	2.33	0.04
FeO*	19.81	0.34	0.86	0.06	33.79	0.59	0.87	0.06
MnO	0.57	0.05	3.99	0.04	0.98	0.03	1.65	0.05
MgO	23.06	0.18	0.40	0.02	10.57	0.13	0.63	0.02
CaO	2.20	0.03	0.58	0.02	4.60	0.35	3.77	0.03
TOTAL	100.54				99.66			

Table A8.4. Estimates of the precision and detection limits of electron microprobe analyses of glassy materials

	MAGF2/01 ¹				MAMBR3/04/1 ²			
	Conc.	Err.	C.V.	D.L.	Conc.	Err.	C.V.	D.L.
SiO ₂	49.04	0.15	0.15	0.01	48.83	0.26	0.27	0.02
TiO ₂	0.64	0.02	1.29	0.02	0.48	0.03	2.93	0.03
Al ₂ O ₃	11.28	0.08	0.36	0.01	10.28	0.13	0.63	0.01
Cr ₂ O ₃	0.49	0.02	2.48	0.03	0.60	0.01	0.99	0.04
FeO*	18.64	0.20	0.54	0.04	17.88	0.40	1.12	0.06
MnO	0.56	0.01	0.67	0.03	0.50	0.03	3.36	0.04
MgO	10.53	0.11	0.53	0.01	12.80	0.08	0.31	0.02
CaO	8.58	0.08	0.48	0.02	8.00	0.06	0.38	0.03
Na ₂ O	0.19	0.02	5.46	0.02	0.61	0.04	3.12	0.03
K ₂ O	0.33	0.03	4.40	0.02	0.12	0.01	5.47	0.02
TOTAL	100.28				100.10			

Notes: 1. 20-second counting times throughout
2. 10-second counting times except for alkalis, which were counted for 20 seconds

plots. As discussed in the text, these trends generally 'mimic' those exhibited by the bulk chemical data for the achondrites obtained by analytical procedures based on standardization more rigorously controlled than is at present possible in microprobe analysis.

A8.6 Detection limits

Theoretical detection limits were calculated at the 99 percent confidence level for each of the oxides listed in Tables A8.2-A8.4 according to the formula given by NORRISH and CHAPPELL (1967). All the values are well above the detection limits except K_2O in one of the plagioclases of Table A8.2, which is just detected. It must therefore be concluded that, in the most calcic plagioclases analyzed (An_{95} - An_{97}), K_2O is not detected, and this is reflected in the appropriate tables in Appendices 2 and 3.

APPENDIX 9

RECALCULATION OF THE BULK CHEMICAL ANALYSES

Although the magnetic extraction of metal from the crushed samples of mesosiderites described in Appendix 6 was very effective, the process was unable to remove all of the metal, as is shown by the presence of moderate amounts of Ni in the analyses (Table 4.3). The incomplete liberation of metal included in silicate grains presumably accounts for this. In addition, the samples retained their content of troilite, which is non-magnetic, and the analyses show S values of up to 6% as a result. These observations apply also to the samples of Estherville and Mount Padbury, which were received as powdered non-magnetic separates (Table 1.1). It was necessary, therefore, to apply a correction procedure to the analyses to make them truly representative of the silicate fractions of the meteorites - to complete the separation mathematically, as it were. It should be noted that chromite is included in the 'silicate' fractions resulting from these recalculations, because no reliable correction can be made for the partitioning of Cr between the pyroxenes present and the spinel phase.

The recalculation procedure assumes that all Ni present is alloyed with Fe in the metal phase, and that all the S occurs as troilite, stoichiometric FeS. The petrographic evidence supports these assumptions. Furthermore, the chemical data (Tables 4.1 and 4.3) show only negligible proportions of chalcophile elements. The average content of Ni in the metal phase of each meteorite analyzed is known, either from published work or from the present investigation. By using these Ni values, which are listed in Table A9.3, Fe can be allocated to the metal phase. Similarly, Fe can be assigned to S to establish the percentage of troilite present in each sample. These amounts, together with the 'loss on ignition' (L.O.I.) and H_2O - values, are

then subtracted from the analysis (see Tables A9.1 and A9.2). However, a further correction must be made to effect a balance between the original and recalculated summations. This is denoted as 'excess O' in Tables A9.1 and A9.2, and represents the oxygen originally allocated to the metallic Fe not accounted for by the artificial concept of a 1:1 alloying process with the available Ni, i.e. the bulk of the Fe not combined with O or S, as Table A9.3 shows.

The following example, using the analysis of the mesosiderite Mincy (Table 4.3), may elucidate the recalculation procedure:

Ni content of metal in Mincy (Table A9.3) = 7.2%

Amount of Fe present in metal = $\frac{92.8 \times 0.470}{7.2} = 6.058\%$

Amount of Fe present in troilite = $\frac{55.847 \times 0.544}{32.064} = 0.948\%$

Total Fe to be allocated to metal and troilite = 7.006%

Remaining FeO in 'silicate' fraction = $16.778 - (7.006 \times 1.2864) = \underline{7.765\%}$

Amount of metal in Mincy = $6.058 + 0.470 = \underline{6.528\%}$

Amount of troilite in Mincy = $0.948 + 0.544 = \underline{1.492\%}$

Amount of Fe assigned to Ni in metal on a 1:1 basis = $\frac{55.847 \times 0.470}{58.71}$
= 0.447%

Amount of Fe in metal originally (Table 4.3) assigned to O
= $6.058 - 0.447 = 5.611\%$

'Excess O' = $(5.611 \times 1.2864) - 5.611 = \underline{1.607\%}$

The data listed in Tables A9.1 and A9.2 represent an intermediate stage in the recalculation procedure. Factors listed in Table A9.4 that were derived from the sub-totals for the 'silicate' fractions of the analyses (Tables A9.1 and A9.2) were used to normalize the data relating to these fractions to 100% (Tables 4.2 and 4.4). The lithophile trace elements also were adjusted accordingly.

Table A9.1. Recalculation of the data of Table 4.1 to 'silicate' and 'non-silicate' fractions

	MALVERN (UCT)	MALVERN (BLM)	BINDA	KAPOETA	MOLTENO
SiO ₂	49.16	48.66	49.98	49.79	49.36
TiO ₂	0.503	0.526	0.234	0.384	0.442
Al ₂ O ₃	10.01	10.61	7.05	8.13	8.95
Cr ₂ O ₃	0.573	0.561	0.745	0.778	0.683
FeO*	17.49	17.68	16.48	16.00	16.78
MnO	0.534	0.520	0.518	0.515	0.523
MgO	11.75	10.98	17.58	15.81	14.01
CaO	8.07	8.46	5.50	6.46	7.20
Na ₂ O	0.31	0.31	0.15	0.29	0.29
K ₂ O	0.039	0.043	0.009	0.011	0.017
P ₂ O ₅	0.058	0.071	0.025	0.045	0.050
	98.497	98.421	98.271	98.213	98.305
L.O.I.	(-1.747)	(-1.829)	(-0.818)	(-0.739)	(-1.072)
H ₂ O-	0.171	0.193	0.189	0.154	0.102
NiFe	0.462	0.385	0.000	0.541	0.433
FeS	0.436	0.935	0.332	0.784	0.809
'Excess' O ⁺	0.119	0.099	0.000	0.142	0.112
TOTAL	99.685	100.033	98.792	99.834	99.761

Notes (applicable also to Table A9.2):

1. FeO* - all 'silicate' Fe expressed as FeO.
2. ⁺ - for an explanation of 'excess' O, see text.

Table A9.2. Recalculation of the data of Table 4.3 to 'silicate' and 'non-silicate' fractions

	MINCY	PATWAR	ESTHER- VILLE	MOUNT PADBURY	VACA MUERTA	EMERY	LOWICZ
SiO ₂	47.46	40.49	47.81	44.32	36.19	49.81	50.12
TiO ₂	0.263	0.182	0.283	0.234	0.214	0.365	0.342
Al ₂ O ₃	6.69	6.35	8.99	6.69	7.14	11.45	10.58
Cr ₂ O ₃	1.474	0.534	0.835	0.863	0.903	0.790	0.767
FeO*	7.77	11.54	11.12	7.99	9.75	7.36	7.41
MnO	0.530	0.448	0.464	0.506	0.354	0.509	0.533
MgO	18.27	12.96	15.77	15.15	10.08	12.02	13.85
CaO	5.29	5.21	6.76	5.20	5.62	8.79	7.97
Na ₂ O	0.22	0.19	0.29	0.15	0.20	0.36	0.31
K ₂ O	0.008	0.000	0.003	0.003	0.010	0.015	0.017
P ₂ O ₅	1.243	0.902	0.524	0.401	1.407	2.134	1.325
	89.218	78.806	92.849	81.507	71.868	93.603	93.224
L.O.I.	(-0.525)	1.163	(-0.583)	0.870	2.771	(-0.455)	(-1.151)
H ₂ O-	0.100	0.052	0.042	0.111	0.137	0.199	0.126
NiFe	6.528	1.061	1.789	6.803	6.034	3.886	4.551
FeS	1.492	18.934	4.943	8.384	16.747	1.113	0.674
'Excess' O ⁺	1.607	0.245	0.422	1.716	1.431	0.961	1.108
TOTAL	98.945	100.261	100.045	99.391	98.988	99.762	99.683

Table A9.3. Average Ni contents of the metal phases of the meteorites whose analyses were recalculated

ACHONDRITES			MESOSIDERITES		
Meteorite	Ave.Ni%	Ref.	Meteorite	Ave.Ni%	Ref.
MALVERN (UCT)	5.20	1	MINCY	7.2	4
MALVERN (BLM)	5.20	1	PATWAR	9.9	4
BINDA	0.44-2.10	2	ESTHERVILLE	9.0	4
KAPOETA	4.25	3	MOUNT PADBURY	6.10	4
MOLTENO	5.08	1	VACA MUERTA	8.8	4
			EMERY	7.0	4
			ŁOWICZ	7.69	4

References: 1 - this work
 2 - Duke (1965)
 3 - Fredriksson and Keil (1963)
 4 - Wasson et al. (1974)

Table A9.4. Factors used in the normalization of the recalculated chemical data on achondrites and mesosiderites in Tables A9.1 and A9.2

ACHONDRITES		MESOSIDERITES	
Meteorite	Factor	Meteorite	Factor
MALVERN (UCT)	1.0153	MINCY	1.1209
MALVERN (BLM)	1.0160	PATWAR	1.2689
BINDA	1.0176	ESTHERVILLE	1.0770
KAPOETA	1.0182	MOUNT PADBURY	1.2269
MOLTENO	1.0172	VACA MUERTA	1.3914
		EMERY	1.0683
		ŁOWICZ	1.0727

Although no attempt was made during the preparation of the achondrite samples to remove the metal phase, the analyses (Table 4.1) showed appreciable amounts of S, and the presence of Ni confirmed the microscopic identification of metal. The recalculation procedure was therefore extended to include the achondrites, as indicated by earlier references to the tables of recalculated data. This step facilitates comparison of the silicate fractions of achondrites and mesosiderites.

FINITA LA COMMEDIA

19 JUL 1983