STRUCTURAL ANALYSIS OF SOME PRE-CAPE FORMATIONS IN THE WESTERN PROVINCE

by

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CONTENTS

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ABSTRACT

The principal objective of the present study was the testing of previous stratigraphic interpretations, particularly in respect of the Klipheuwel and Franschhoek formations, by means of attention to hitherto generally neglected structural or tectonic aspects of the pre-Cape rocks.

In the Worcester area, it was found that the structural sequence across the so-called Malmesbury-Klipheuwel unconformity (de Villiers, Jansen and Mulder, 1964) is the reverse of that previously postulated, and the controversial correlation of the lower (previously upper) formation with the Klipheuwel Group cannot be maintained. The deformation of the pre-Cape formations is considered to have taken place in four stages or phases, labelled O, M, X and K in sequence. The Early phases, O and M, are responsible for the broad stratigraphic pattern, while the Late phases, X and K, locally modify the earlier structures and have little or no effect on the distribution of rock types. An important tectonic discontinuity, or slide, apparently separates the upper formation from the two lower units, and close to the much younger Worcester Fault, a pre-Cape thrust has brought sheared and mylonitised granitic rocks to rest against the former.

Structural relationships at Franschhoek are confusing, but in Kaaimansgat structures of Early and Late generations can be distinguished. In these southern areas the deformation of the rocks is again such that they clearly cannot be correlated with the Klipheuwel Group. However, their close association with older, sheared granitoid rocks and caraclasites - one of the main points upon which the Franschhoek-Klipheuwel correlation was based - is not in dispute. Although granite studies were not included in the scope of this work, one of the incidental results has been to widen the field of the older granite problem to include Kaaimansgat and Worcester as well as Franschhoek.

The relationships of the pre-Cape formations treated in this work - called the Boland Group (after Rabie, 1948) - to the "Malmesbury" formations farther west is still problematical. The deformation of most of the pre-Cape formations in the Western Cape Province, Boland and "Malmesbury" alike, was apparently effected during a major orogenic event in upper Proterozoic - lower Paleozoic times. The term "Saldanian" is proposed as generally descriptive of this event and the structures which it has produced.

INTRODUCTION

1. General Statement

True South African geology is said to begin with Andrew Geddes Bain, who, like William Smith - the Father of English Geology - was a road-maker. Inspired by Lyell's book, "Principles of Geology", Bain (in his own words)

> "made the first attempt to give the varied formations of the Cape Colony a local habitation and a name, without the shadow of a foundation to commence upon but what his own observation suggested. He had no predecessors whose labour he could avail himself of, nor contemporaries whose assistance he could solicit, but for fourteen years was groping about in the dark, as it were, through virgin fields hitherto quite untrodden, being, as far as Geology goes, a *terra incognita*". *

Bain recognised that unconformably beneath his "Silurian" and "Carboniferous" series in the south-western Cape lay a series of "Clayslate and Gneiss with intrusive Granite" (Bain, 1856). This unfossiliferous and undifferentiated series made up the basal portion of the northern Cape Peninsula, the greater portion of the western lowland (Sandveld and Swartland) areas, and also appeared as inliers in the Boland.

Now, 112 years since the first publication of Bain's observations, the basement formations of the Western Province remain, in many respects, an enigmatic *terra incognita* surrounded by controversy, the immediate ground of which is not difficult to appreciate. The younger Table Mountain Group of massive quartzitic sandstones is the geological element of greatest physiographic importance in these regions; it forms the superstructure of the Peninsula and builds the rugged mountains of the Boland. Beneath this, the basal series of the Cape System, in scattered areas of depressed and generally subdued relief, the obviously complex pre-Cape formations are very rarely well-exposed and usually highly weathered. In short, it is the poor and fragmentary nature of the pre-Cape outcrop that has constituted the greatest obstacle to progress, for even the most basic information about structure and stratigraphy is here hard won.

The pre-Cape rocks include a fairly large variety of lithological types; quartzofelspathic, chloritic and micaceous schists, phyllites and slates, some shales and mudstones, limestones and dolomite, various quartzites, arkoses, conglomerates, greywackes and subgreywackes, some extrusive greenstones, minor basic intrusives, and various types of Cape granite. Although their distribution is, in spite of unfavourable exposure, by now fairly well known, the problem of establishing an acceptable stratigraphical order in these rocks has been a particularly refractory one, and the subject of widely differing approaches.

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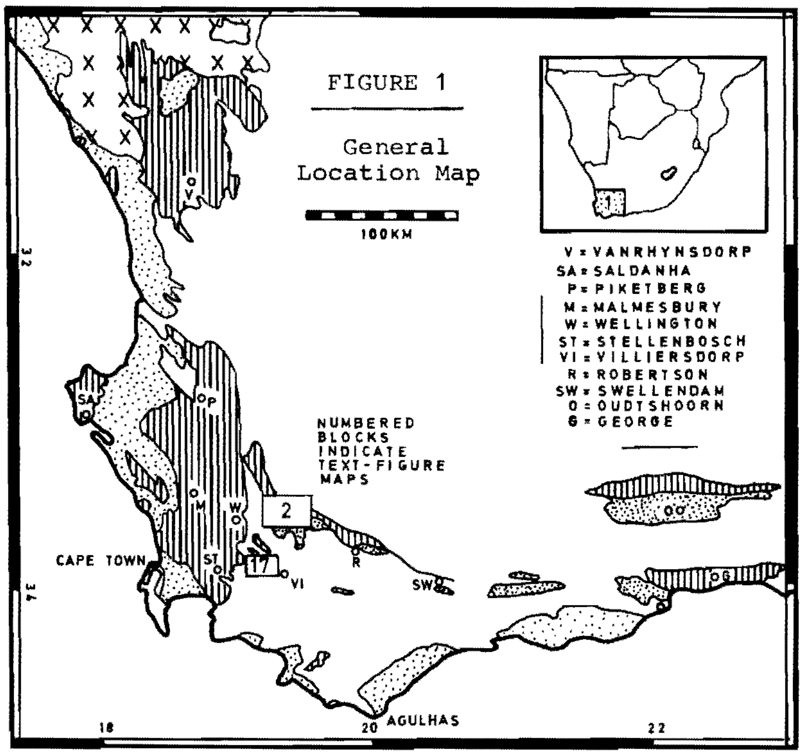
* From the original manuscript of the introduction to his paper "On the Geology of Southern Africa".



Vertical ruling indicates Upper Proterozoic - Cambrian "Malmesbury" and associated formations

2. Historical Review

a. Bain to the Cape of Good Hope Geological Commission : (1856-1909)

In 1872, E.J. Dunn named the Clay Slate Series of Bain (1856), the "Malmesbury Beds", and the name "Malmesbury Series" was retained with the establishing of the Geological Commission of the Cape of Good Hope in 1895. Shortly after this, investigations were extended beyond the Western Cape, and the "Cango Series" was said possibly to post-date the so-called Malmesbury Beds, and their intrusive granites, of the George area (Corstorphine, 1898, p. 7-13). In the same year, E.H.L. Schwarz (1898, p. 28) described the apparently unconformable Honig Berg (Heuningberg) conglomerates. The term "Ibiquas Series" was introduced after investigations in the Vanrhynsdorp Division (Rogers and Schwarz, 1900) had indicated that a pre-Cape sequence younger than the so-called Malmesbury Series of that area might exist. Rogers (1905) thought that the Heuningberg Beds might belong to the Cango Series and later Rogers and du Toit (1909) referred them also to the Ibiquas Series. At the same time they separated the "French Hoek Beds" from the Malmesbury Series and also compared these to the Ibiquas Beds.

b. The intermediate period : (1910-1949)

The generally accepted two-fold division of the pre-Cape into an older Malmesbury Series and a younger (French Hoek - Cango -) Ibiquas Series, both of which were regarded by Rogers (1911) as "Nama System" representatives, was somewhat discredited when du Toit compared the beds of the Heuningberg and Klipheuwel vicinities to the Matsap Beds, separating them from the French Hoek Beds on account of their "colouring, arenaceous character, and unsheared condition" (1926, p. 162). In this he was supported by Haughton's work (1932; 1933) on the Cape Town Sheet, on which a division of the pre-Cape into Malmesbury, French Hoek and Klipheuwel Beds was proposed. Haughton, however, was uncertain about definitively divorcing the French Hoek Beds from the Malmesbury Series.

Between 1930 and 1945, most areas of the pre-Cape were intensively mapped, first by post-graduates from Rhodes University working in the eastern areas (McIntyre, 1932; Amm, 1934; Frankel, 1936), and later by post-graduates from Stellenbosch University (de Jager, 1941; Rabie, 1948; Potgieter, 1950a, 1950b; and others). This activity resulted in a strengthening of a correlation of Cango and Malmesbury beds, and later Brink (1950) effectively removed the term Ibiquas Series from circulation by demonstrating that the so-called Malmesbury and Ibiquas of the Nuwerus area were together equivalent to the "Schwarzkalk Series" of the Nama System.

Working in the Malmesbury vicinity itself, L.P. Rabie (1948) distinguished three formations, to which he applied the names "Swartland", "Boland" and "Heuningberg". The most interesting feature of Rabie's work is his division, by the application of structural methods, of the Malmesbury Series into Swartland Formation and Boland Formation. Scholtz (1946), reporting Rabie's (uncompleted) work, recorded that

> "His research work has ...... disclosed the existence of extensive outcrops of sediments younger than the Malmesbury which are tentatively correlated with the Klipheuwel Series" (Op. cit., p. 1i),

referring, presumably, to the Heuningberg Beds. On a "Geological Map of the Pre-Cape Beds in the Worcester - Swellendam Mountain Foreland" (Univ. Stell., 1948), the description, Boland Formation, is applied to "Malmesbury" beds apparently regarded by Scholtz (1946) as Cango correlatives.

At this time, the consensus regarding the Malmesbury Series was that it was probably to be associated in some way with the Nama and Transvaal Systems, and that it was probably of late-Precambrian age. However, new information from the formations of Namaqualand and the Richtersveld (Lamont, 1947; Söhnge and de Villiers, 1946) led to the view, expressed first by Truter (1949, p. 1i), that the Malmesbury formations (French Hoek and Klipheuwel excluded) were the equivalent of the newly-created Gariep System, which was then considered to be of Archaean age.

c. More recent work : (1950 to present)

After mapping the pre-Cape terrains bordering on Haughton's and Rabie's areas, J. de Villiers (1956; de Villiers, Jansen and Mulder, 1964) modified the stratigraphic schemes of both earlier workers. Portions of the Boland Formation were, with the Swartland, retained in the "Malmesbury Formation", while the greatly extended "Klipheuwel Formation", included the Heuningberg Beds and the remaining portions of the more severely deformed Boland Formation. The formations of the Franschhoek area were also included in the "Klipheuwel Formation" despite Haughton's categorical statement that "the Klipheuwel Beds must definitely be distinguished from the older French Hoek Beds" (1933, p. 81). To support this extension of the Klipheuwel, based among other things on general lithological resemblances, de Villiers (1956, p. 81) postulated a front of folding separating little-deformed and highly deformed " Klipheuwel" strata. The "Malmesbury Formation" was correlated with the Gariep System, and considered to be of Archaean age, or at least older than 1100My (de Villiers et al., 1964, p. 24), while the new "Klipheuwel Formation" was correlated with the presumed Upper Proterozoic Loskop System of the Transvaal (de Villiers, 1956; D.J.L. Visser, 1957; de Villiers et al., 1964).

In more recent years it was becoming increasingly apparent that this concept of the pre-Cape was not wholly satisfactory. Apart from the contradictory evidence yielded by various radiometric ages from the south-western part of Southern Africa (cf. Nicolaysen, 1962, p. 594-5; Martin, 1965, p. 84; Allsopp and Kolbe, (1965), continuing field research revealed some further inconsistencies. H.N. Visser (1962, p. 30) drew attention once more to the apparent unconformable relation of the Heuningberg beds to the surrounding phyllites and slates, and later (1964, p. 17) recorded that the lithological nature and structure of the French Hoek Beds and the type area Klipheuwel are so markedly different that these formations probably cannot be correlated. For the pre-Cape tectonites of the Malmesbury district, Newton (1966, p. 17) noted that "... it appears that the "Malmesbury" includes at least two groups of rocks; one, probably older, showing considerable metamorphism and three phases of deformation, and one, presumably younger, showing virtually no metamorphism, and only two phases of deformation..."; which broadly corresponds to the division, on Rabie's (1948) map, of the deformed Malmesbury into Swartland and Boland formations.

3. Present Investigation

Briefly then, an initial phase of geological pioneering in which the term "Malmesbury" was applied more or less indiscriminately to all pre-Cape formations in the south-western Cape Province was succeeded, after 1897, first by a period in which a broad two-fold grouping of the pre-Cape was favoured, and then, after 1926, by a period in which a three-fold grouping of pre-Cape formations was generally accepted. Sometime after 1950, however, the two-fold division came to be restated (in different terms, of course), but could not altogether be reconciled with observations which tended to suggest even greater stratigraphic fragmentation of the so-called "Malmesbury".

This project is concerned with aspects of "Malmesbury" structure as a possible aid in the solution of these stratigraphical problems. In particular, it deals with two important features which have been described from the pre-Cape of Sheet 3319C (de Villiers *et al.*, 1964). These are: (i) the unconformity between folded "Klipheuwel" and "Malmesbury" in the area north-west of Worcester and (ii) the sedimentary contact of the so-called French Hoek Beds - correlated with the Worcester "Klipheuwel" via the pre-Cape beds of Elands Kloof - upon a so-called "post-Malmesbury" granite (*op. cit.*, p. 25).

The terrains treated in this work thus include (i) the pre-Cape outcrops in the foreland of the Hex River Mountains north and north-west of the town of Worcester, (ii) the pre-Cape beds of the Slanghoek Basin, in the mountains between Worcester and Wellington, (iii) the formations exposed in the Franschhoek Valley and, (iv) the large pre-Cape inlier, Elandskloof, in the mountains north of Villiersdorp. The first two areas are separated from the latter by about 24 kilometres of rugged mountainland in which some smaller inliers, in the Wemmershoek- and Dutoitsberge, occur. This separation of the pre-Cape exposures with which this project is concerned greatly hampers structural and stratigraphic intercorrelation, and has made it necessary that the structure and stratigraphy of the northern outcrops (Worcester and Slanghoek) be considered quite independently of that of the southern areas (Franschhoek and Elands Kloof).

Another inhibiting factor in the present work is, of course, the paucity and highly-weathered nature of the pre-Cape outcrops in each of these areas. This is extreme over most of Slanghoek and Franschhoek Valleys, and also over great parts of Worcester and Elands Kloof exposures. At Worcester, an area of some 100 sq. km. between the Hex River, on the east, and the smaller stream, Jan Dutoitsrivier, on the west, provided the best subject for detailed structural analysis, while the Elands Kloof analysis proved somewhat less satisfactory.

In the following pages, therefore, the description of the pre-Cape formations of Sheet 3319C falls into two parts. Part I is concerned with the pre-Cape formations in the vicinity of Worcester and, in particular, with a detailed structural analysis of these formations in the mountain foreland terrain immediately north of Worcester. Part II is concerned with the pre-Cape formations in the vicinities of Franschhoek and Villiersdorp.

4. Acknowledgements

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PART I

THE PRE-CAPE FORMATIONS IN THE VICINITY OF WORCESTER

A. INTRODUCTORY REMARKS

1. Previous work

The history of recorded geological mapping in this district dates back to 1896 when E.H.L. Schwarz commenced work in the region between Tulbagh and Worcester. Earlier E.J. Dunn (1873) had correlated the rocks near Worcester with the "Namaqualand Schists" on his famous map. Schwarz (1896) was the first to record the presence of a "huge fault" just north of Worcester which brought "Malmesbury Beds" into contact with Ecca Beds. In a later summary of his work (Schwarz, 1905), he gave a very brief description of the pre-Cape rocks of the vicinity. The occurrence of granitic and mafic rocks near Brewelskloof had also attracted early attention (Rogers and Schwarz, 1898b).

R.H. Rastall (1911) published a study which had as its principal subject the origin and age of the Worcester Fault, but which dealt in some detail with the lithological character and structure of the "Malmesbury Series" and its associated intrusive rocks in the area just east of the Hartebeest River. It is of interest to note his mention of a "very common strain-slip cleavage", observed under the microscope and on a larger scale in the pre-Cape terrain (Rastall, 1911, p. 709).

In 1942 a project, involving the detailed mapping of the pre-Cape formations in the foreland of the Hex River and Langeberg mountain ranges by post-graduate students of the University of Stellenbosch, was initiated under the direction of Prof. D.L. Scholtz. On the "*Geological Map of the Pre-Cape Beds in the Worcester - Swellendam Mountain Foreland*" (Univ. Stell., 1948), these rocks are shown as belonging to a "Boland Formation" (Rabie, 1948), divided into an upper group, comprising greywackes and conglomerates, and a lower group consisting of a variety of lithological types, including quartzites, arkoses, greywackes and carbonate rocks.

C.T. Potgieter (1950a) examined an occurrence of pyrophyllite at Waaihoek, just west of the Jan Dutoits River; in his brief description of the surrounding geology and structure, he refers to evidence of a "second period of deformation of the Malmesbury rocks" in this region (*op. cit.*, p. 230).

Soon after this, J. de Villiers mapped the area now under discussion as part of the preparation of Geological Survey Sheets 3319C and 3419A (de Villiers, Jansen and Mulder, 1964). A resumé of results, emphasising the structural peculiarities - the pre-Cape and Cape fold "syntaxes" - of the region, appeared soon afterward (de Villiers, 1956). A fundamental change in geological interpretation, involving the separation of the pre-Cape tectonites into two formations, "Malmesbury" and "Klipheuwel", belonging to entirely different cycles of sedimentation and diastrophism, is the major feature of this work.

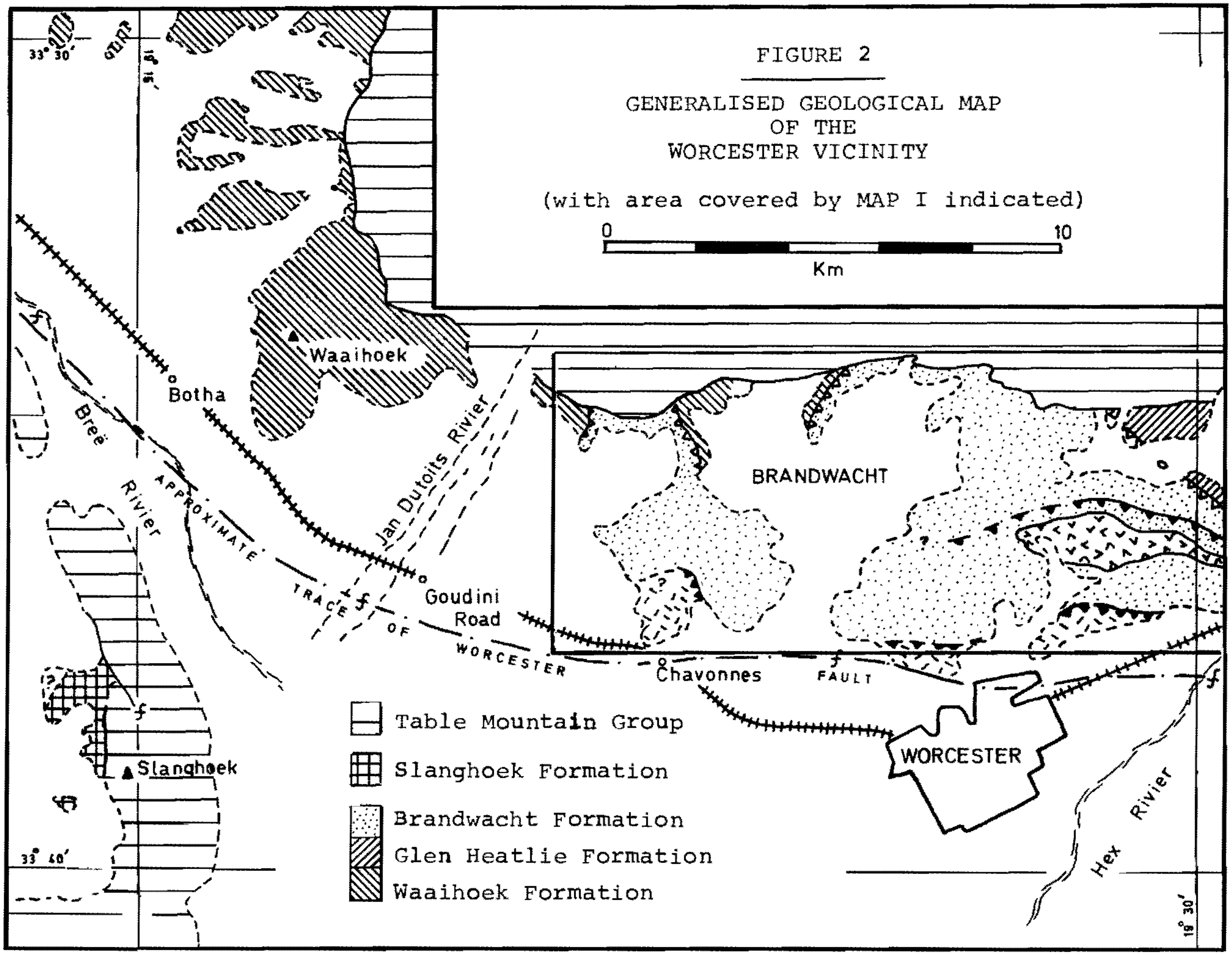

FIGURE 2

GENERALISED GEOLOGICAL MAP
OF THE
WORCESTER VICINITY

(with area covered by MAP I indicated)

Recently local studies of some features have been carried out as undergraduate projects. Hartnady (1966) studied the "Malmesbury-Klipheuwel" unconformity below Chavonnesberg, and Marsh (1967) described the folding of the "Klipheuwel" formations below Waaihoek Peak.

2. Description of the formations

Bearing in mind the very poor conditions of outcrop, the generally fine-grained nature of most of the rock types (which makes them unsuitable for detailed petrographic study), the absence of reliable markers, as well as the overall structural complexity, it will be appreciated that the establishing of a very detailed stratigraphical succession is probably an impossible task. Nevertheless, a broad stratigraphical grouping of the rock types, on the basis of overall lithological characteristics and distribution, seems possible. In this investigation, as in those which have preceded it, three such formations have been recognised: in the west, the " Waaihoek Formation"; in the centre, the "Brandwacht Formation"; and in the east, the "Glen Heatlie Formation". (Refer to Fig. 2). In the south-eastern part of the Slanghoek Valley, which is not considered in detail here, a formation consisting of quartzites and purplish mudstones is quite obviously not to be associated with the tectonites of the main foreland outcrop, and there can be very little doubt about its correlation with the Klipheuwel Formation proper.

The Waaihoek Formation, named for its development about the trigonometrical beacon and below the peak of that name, corresponds to the "Klipheuwel Formation" of de Villiers et al., (1964). It is characterised by a number of bands of massive white quartzite which, from the path leading up to the ski hut on the slopes of Waaihoek Peak, can be observed to be thrown into spectacular, near-isoclinal folds. Also characteristic of this formation is the wide development of fine-grained phyllites or slates, which are generally of a dark greyish colour in a fresh, unaltered state. Rock types of a wacke nature also occur here, but appear to be subordinate to the dark pelites.

Wackes, and rock types of a generally immature nature, appear to be somewhat the more distinctive component of the Glen Heatlie Formation which, within Sheet 3319C, is poorly exposed in a small area just west of the Hex River; it is named after an old farm in the vicinity. Though similar in some respects to the fine-grained rocks of the Waaihoek Formation, the slates of the Glen Heatlie Formation tend to have a more drab and gritty appearance, and include irregular intercalations of impure arenaceous material or subgreywacke. The formation in fact corresponds to the so-called "Middle Greywacke" of the Stellenbosch map; on Sheet 3319C (de Villiers et al., 1964) it is placed, together with the formations immediately to the west, in the upper "Malmesbury Formation", but is distinguished as a more "shaly" variety. It must therefore be conceded that, though not very pronounced, there are differences - apart from the regional absence of thick mature quartzites - which definitely distinguish the Glen Heatlie Formation from the Waaihoek Formation, and also from the Brandwacht Formation, with which it is in contact in the east.

The Brandwacht Formation, which makes up the greater portion of the terrain just north of the town of Worcester is quite distinctive. The rocks are grey-green or dark grey when fresh, but weather to a drab brown; they are quite legitimately described as greywackes. The dominant lithology appears to consist of a fine matrix of sericite, chlorite and quartz enclosing generally sparse but varying amounts of quartz grains, usually less then 0.5 mm. in size and quite angular. Indurated matrix is nearly always dominant and sometimes forms fine-grained bands, of varying thickness, in the rock. Graded bedding may, in places, be a feature of this lithology, but the poor quality of most of the outcrop, and the metamorphism of the rocks, does not generally allow unequivocal identification of such sedimentary structures. Although greywackes which may roughly be described as medium-grained appear to predominate, there is quite a wide development of finer, argillaceous types and also coarser quartz wacke varieties. A pebbly greywacke, usually with associated irregular lenses of conglomerate, most often consisting of a wide size-range of pebbles and cobbles apparently torrentially assembled in a "greywacke" matrix, is also commonly encountered. Such a conglomerate is most prominently developed at the apparent base of the Brandwacht Formation.

There is a suspicion that this basal conglomerate of the Brandwacht Formation if not wholly sedimentary in origin, but that, in part at least, it may represent a type of tectonic melange (Hsu, 1968). In places it appears that fragments of the underlying phyllitic material have been tectonically detached and incorporated, in a severely distorted state, in a highly sheared groundmass of "phyllitic" metagreywacke.

Mafic and felsic rocks, which have been described before as intrusive into the Brandwacht Formation (Rogers and Schwarz, 1898b, p. 83-84; Rastall, 1911, p. 710-712; de Villiers et al., 1964, p. 20-21 & 23), were considered to be out of the scope of this project. However, these so-called intrusives certainly pre-date the main regional deformation of the surrounding formations; the s_1 foliation is developed in them also.

In the case of the Brewelskloof mass of "biotite-eucrite" (de Villiers et al., 1964, p. 21) and small, isolated masses of "greenstone" and metadoleritic material, the postulate of intrusion is probably correct, though Rastall (op. cit.) noted some petrographic features which suggested an extrusive origin. The northern contact of the large mass, where it is exposed, does in fact appear to be parallel to the original bedding in the Brandwacht Formation.

On the other hand, the granitoid rocks in the south are not, and probably never were, intrusive into the Brandwacht Formation. In the Brewelskloof area, where the contact with the Brandwacht metagreywackes is well-exposed, it is clearly tectonic. The "granite" at the contact has been reduced to a fine quartz-sericite rock - a variety of mylonite - in which porphyroclasts of quartz gradually become more conspicuous towards the more gneissic interior parts.

B. STRUCTURAL ANALYSIS

1. The "geometrical approach"

To the degree that previous workers tended to concentrate on the conventional mapping of lithostratigraphy while virtually excluding detailed observations of tectonic data, so did their approach to the more intractable problems of the pre-Cape formations suffer. For it is clear that the larger proportion of these rocks has been subjected to widespread, if low-grade, orogenic metamorphism, and it is in this respect that one of the principal roots of the difficulties lies. While a "stratigraphical approach" (Weiss, 1959a, p. 12) - in which major structures are deduced by correlating assumed stratigraphical columns - proves adequate for the study of gently folded or fossiliferous rocks, as a method in the analysis of metamorphic terrains it is usually invalid. The simple relationships between structure and stratigraphy, amounting to their virtual synonymity in higher tectonic levels, do not generally hold in the deeper structural regimes.

The methods of the "geometrical approach", on the other hand, were first evolved in the Swiss Alps in the early part of the present century (Christensen, 1963; Wilson, 1967). Beginning with the appreciation of the Glarus and Pre-Alpine structures by Bertrand (1884) and Schardt (1893) respectively, Lugeon (1901) unravelled the principal elements - the Morcles, Wildhorn and Diablerets nappes - of the High Calcareous Alps by combining with the stratigraphic relations the geometric observation that the forms of the folds persist in their axial direction. In his classic paper on the Pennine Alps, a terrain where there is little or no stratigraphic control, Argand (1911) laid emphasis on the "principal of axial continuity" as an aid in structural inference.

Leaving the Alps, Wegmann (1929) applied an axial projection method to Finnish Shield areas, in which relief is low and the continuity of fold profiles in the axial direction cannot be observed directly. To test for axial continuity under such conditions, he used the geometrical method of plotting field measurement of structural data on stereographic projections. Wegmann's methods, which are the prototype of modern structural techniques, were introduced to the Scottish Highlands by McIntyre (1951).

Recent structural descriptions from the latter terrain (Ramsay, 1957; Weiss and McIntyre, 1957; and many subsequent papers), from the Pennine zone of the Alps, and from metamorphic terrains in many other parts of the world, have tended to play down the strictly "cylindrist" concepts of the Swiss school, and have emphasised the geometrical heterogeneity of fold-axial structures that can arise from the superposition of two or more systems of folding. The evolution of the method of subarea analysis (cf. Ramsay, 1957), involving the detailed systematic mapping of minor structures and their preferred orientations, is a product of this work. Sutton (in Ramsay, 1957, p. 307) remarked that a " ... striking feature of this research is the way in which the attitude and form of practically every observed small structure can be related to the development of some much larger fold... ".

2. Structural Geometry

a. Minor tectonic structures

This section is concerned primarily with the definition of the minor structures that can be observed in the field, and not with the details of their genesis. As far as possible, therefore, the terminology employed is purely descriptive and where terms occasionally carry genetic connotations they do so more for a purpose of familiar illustration. The term "foliation" is preferred as a general term for all reasonably penetrative planar structures, and "linear structure" denotes lineations, minor-fold axes, mullions and so on; the usage is essentially that advocated in Whitten (1966a, p. 216-321), but some terms have been indexed with primary references. The end to which all of this is directed is, of course, the objective labelling of all planar and linear structures as s_1, s_2, ... s_n and l_1, l_2, ... l_n respectively, according to their character and/or chronological succession.

(i) Planar structures: Generally original bedding planes (s_0) are not a very obvious structure in this terrain. A ubiquitous "regional foliation" (s_1) is a far more conspicuous structure than sedimentary bedding, and in fact has often been equated with it in the observation that parts of the pre-Cape terrain are characterised by "bedding foliation" or "schistosity parallel to bedding" (e.g. de Jager, 1941). This matter of the relationship between the earliest surface of heterogeneity, the sedimentary bedding, and the most prominent tectonic element, the penetrative regional foliation, has important ramifications which will be elaborated below; for the moment, it is sufficient to note that, in this investigation, planes of lithological heterogeneity were labelled s_0 only where their angular discordance with an early penetrative foliation could be seen or demonstrated.

The above-mentioned s_1, although everywhere present, is by no means a uniform structure. There are two factors contributing to the striking physical variability of s_1, one of which is the rather local effect of lithological competence, well-displayed in some small-scale fold structures. In very fine-grained lithologies, the foliation looks like a typical slaty cleavage and may show all the variety of gradation to a fracture cleavage as grain size and competence increase; in some arenaceous and conglomeratic greywackes even the latter type may be hardly developed. In conjunction with this, the slight geometrical effect of cleavage refraction can sometimes be noted. On a larger scale the effect of lithology on the expression of s_1 is illustrated to an extreme degree by the massive quartzites of the Kleinberg and Waaihoek regions, just west of this area, where only the surrounding phyllites display s_1.

In the Brandwacht Formation, there is in addition a clear, regional, variation in the character of s_1 which apparently has little to do with the purely lithological factor. The examples of slaty and fracture cleavage described above correspond to fairly typical varieties of axial-plane foliation (Whitten, 1966a, p. 221), intersecting bedding at an angle, even on the steeper minor-fold limbs. Over a considerable area, however, s_1 is apparently parallel to bedding, though close inspection reveals that it intersects rare bedding remnants at a very acute angle. Here it has a generally schistose and almost phyllonitic appearance in places; the greywackes of these parts have clearly undergone a significant degree of dynamic reconstruction. The "bedding foliation" is in fact a form of "pseudo-bedding" (Whitten, 1966a, p. 182), and s_1 may here be described as a transposition structure (op. cit., p. 181-ff).

A crenulation foliation (Rickard, 1961; Whitten, 1966a, p. 230) cutting s_1 is associated with minor and major folds of the latter, which are the most conspicuous of the pre-Cape fold structures. Unlike the prevasive s_1, this secondary foliation (s_2) is localised in its development and is penetrative only on certain scales. It too has a highly variable physical character. According to its position within minor and major flexures of s_1, s_2 may change from a fracture cleavage - really a close-spaced jointing - through a typical variety of crenulation foliation to a "phyllitic" schistosity which, in some cases, is virtually indistinguishable from s_1, and only on very close inspection can be seen to be a transposition of the latter. "Fracture" varieties of s_2 generally strike NNE, while the best-developed "phyllitic" varieties strike ENE, or even near E-W. It is this phenomenon alone which accounts for the quite large scatter of s_2 -poles in Fig. 5C, also schematically illustrated in Fig. 16. Phenomena resembling this have been described for late crenulation foliations on a number of occasions (Hoeppener, 1956; Weiss and McIntyre, 1957; cf. also Turner and Weiss, 1963, p. 464-6).

Some of the kink-bands (Dewey, 1965) and joints commonly encountered throughout the area can be related on geometric grounds to s_2. Near Meiringsberg, similar, poorly-developed, structures bear a roughly conjugate relationship (Johnson, 1956; Ramsay, 1962) to s_2, and have been labelled s_3; they have a strike and dip of about 140/70SW. Apparently still later than s_2 or s_3, though nowhere developed in very close proximity to either, and cutting s_1 only, are very rare axial-plane fractures or "shears" (s_4) with a shallow northward dip rarely exceeding 30°. The strike of s_4 is somewhat variable about E-W, and probably depends to a certain extent on the attitude of s_1 in which it has formed. The s_4 cleavage is very sporadically developed, and no great attention has been paid to it in this investigation.

(ii) Linear structures: Because linear structures in areas of repeated folding are generally composite fabric elements (Turner and Weiss, 1963, p. 41) and thus very sensitive to the influence of initial fabrics, and because of the great variety of forms which they can show, they are not usually as easily pigeon-holed as foliations. In the Worcester area, intersection lineations, "pencils" and mullions, crenulations, striations, elongated pebbles, and minor-fold axes of diverse generations and orientations all fall into the linear structure category. The most useful distinction in practice was found to be between Early linear structures - those associated with the development of s_1, and Late linear structures - those associated with planar structures which post-date s_1.

The Early linear structures (l_1) presented the greatest problem to objective operational definition of any of the mesoscopic fabric elements in this area, mainly because of their great variety of form and orientation. In those parts where s_0 can definitely be distinguished from the imposed regional foliation l_1 takes the form of a penetrative intersection lineation. The trend of l_1 lies reasonably close to the strike of s_1; in other words, the lineation does not pitch at a great angle in the foliation plane. In the domains of "phyllonitic" metagreywacke, however, l_1 appears as a very penetrative and fine striation or mineral lineation on s_1; the long axes of pebbles and occasional mullion-like structures parallel this lineation. A few observations show that it also marks the rough axial trend of Early minor folds and s_1/s_0 intersections. Here l_1 pitches very steeply, practically down the dip of s_1. This description refers to the two extremes, as it were, of Early lineation development; geometrically at least, there is a whole range of variation between.

The confusing feature about l_1 is that it has these two essentially different aspects, one of "intersection", and the other of "stretching", each dominating a different part of the Brandwacht Formation. The latter aspect, that of elongation or extension of the rock material in the plane of s_1, is of less importance to the present work than the changing orientation of the Early intersection lineation and fold axes. The maximum strain extension (X) in the rocks does not appear to be subject to significant changes in orientation over the area; it seems rather to be increased or accented in those parts where the intersection lineation virtually coincides.

It was not considered necessary to erect separate subcategories in l_1 (l_{1X} and l_{1B}, say) to take account of these differences since, with the accenting effect just mentioned, l_{1X} can in general be observed only where it can, for all practical purposes, be considered geometrically equivalent to l_{1B}.

The Late linear structures, l_2, l_3 and l_4, are not generally penetrative structures, and are associated with the foliations - s_2, s_3 and s_4, respectively - which cut s_1. The best-developed of the Late linear structures is l_2, an s_2/s_1 intersection lineation often represented by "pencil"-like cleavage mullions, such as those seen in the vicinity of the Shangri-La trigonometrical beacon. The same linear structure is occasionally seen as axes of small crenulations on s_1 which have s_2 for an axial-plane. In the Olifantsberg area l_2 and l_1 have subparallel orientations, but are not easily confused; examples of l_1 slightly oblique to l_2, and accordingly deflected across small Late flexures, have been seen here.

Other Late linear structures, l_3 and l_4, are not at all prominent, and are not so much represented by the intersections of s_3 and s_4 with s_1 (for these later foliations are themselves scarcely developed), as by axes of irregular and inconstant flexures in s_1. The orientation of l_3 broadly corresponds to that of l_2, though the former trends more east of south while the latter trends more to the west of south. The orientation of l_4, however, is quite different; it is subhorizontal and trends roughly E or W. Characteristically, it shows as fine "crinkling" on s_1.

(iii) Minor folds: In the previous section, minor folds were briefly touched on in connection with their axial attitudes, and their geometrical significance as linear fabric elements. At the same time the terms "Early" and "Late" were introduced into the discussion as a first step towards a clear separation of the different generations or phases of pre-Cape structure. The use of these terms may be better understood if they are defined in relation to the minor folds of different size, shape and style (Turner and Weiss, 1963, p. 112-7) which can be seen in the field.

As used here, Early folding refers mainly to ${B_{s_0}}^{s_1}$ folds - that is, folds of s_0 to which s_1 is axial-planar (op.cit., p. 131). Similarly, Late folding refers specifically to the folding of s_1, as in ${B_{s_1}}^{s_2}$, ${B_{s_1}}^{s_3}$ and ${B_{s_1}}^{s_4}$ structures*, the first-mentioned of which is by far the more important. Thus folds formed before or with s_1 are Early folds, and folds formed after s_1 - and most obviously displayed in the folding of s_1 - are Late folds.

Early minor folds. B_1 structures are not very commonly encountered, but they appear to vary quite considerably in shape and style as well as attitude. This is perhaps surprising in view of the commonly-accepted assertion that folds "... of a given generation in a given rock type usually can be correlated by identity of style more than by any other character.." (Turner and Weiss, 1963, p. 112). Though no quantitative study of fold shape (Ramsay, 1967, p. 359-72) or profile-geometry (Whitten, 1966b) has been undertaken here, it seems fairly safe to say that such a study of the Early minor folds - if it could overcome the major obstacle of poor and limited exposure - would prove interesting.

The contrast in Early fold style falls between larger (metre-scale), open to close (cf. Fleuty, 1964a) structures on the one hand, and small (centimetre-scale), tightly appressed structures on the other. While the limbs of the former type are usually preserved, in the latter case both are generally sheared out, and the structures appear as "rootless" mullions or ill-defined intrafolial folds (Turner and Weiss, 1963, p. 117). The sketches in Fig. 3 illustrate the extremes of contrast.

Some of the Early minor folds could be described as being of a "concentric" type, though as Ramsay (1967, p. 371) notes, "... the two models around which much fold classification has centred in the past are but two unique types in a whole field of possible geometrical models...". Closer examination would probably reveal that these folds are of atype lying between the ideal concentric and similar models, and occasionally approximating, with varying degrees of perfection, to the ideal similar shape.

The different styles of B_1 fold naturally show a broad geographical segregation. The folds of intrafolial type are confined to those parts of the terrain in which s_1 is a transposition structure, while the more conspicuous "concentric" folds are, not unexpectedly, found where s_1 has a conventional, slaty or axial-plane aspect. Axial attitudes are also significant; the more open type generally has only a gentle or moderate pitch in the plane of s_1, but the intrafolial variety usually has a reclined (Sutton, 1960) Fleuty, 1964a) attitude. There is therefore a direct correlation between B_1 fold style and the variability of s_1 and l_1 described in the previous sections.

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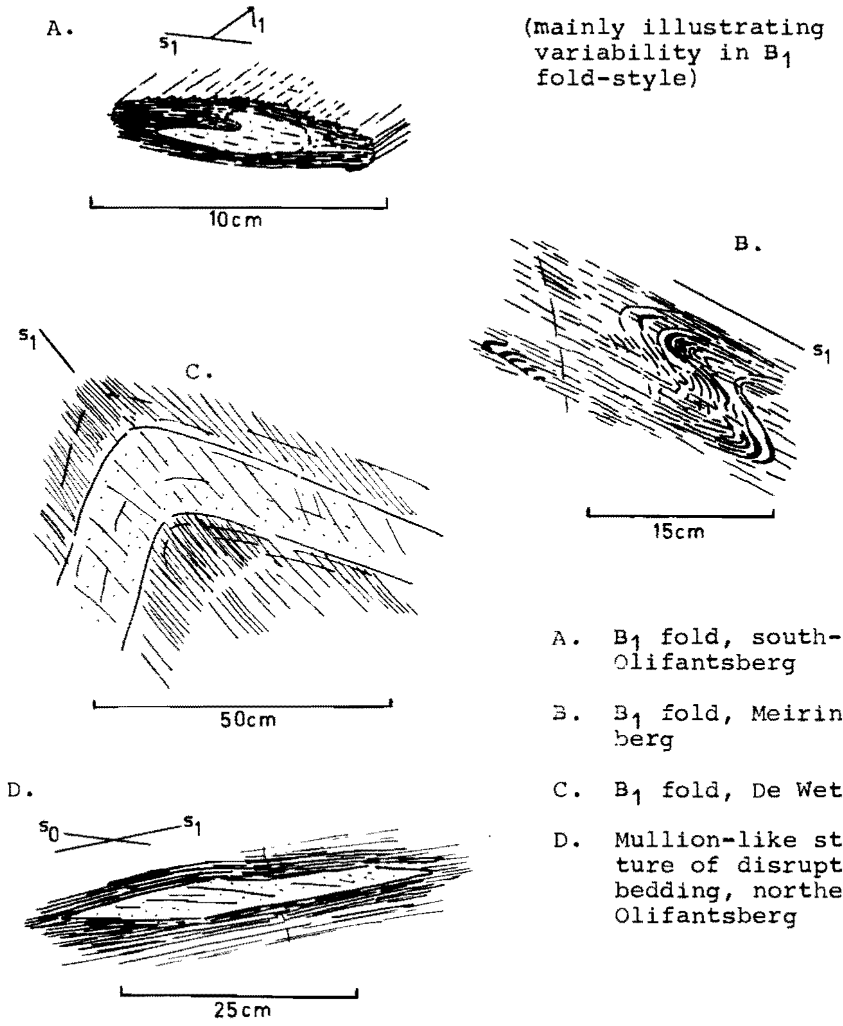
* As this minor-fold shorthand, while having the advantage of precision, is awkward and inconvenient to insert in the present typescript, the further abbreviations B_1, B_2, B_3 and B_4 will be used instead. The subscript refers to the respective axial-plane foliation.

FIGURE 3

Sketches of Early minor structures

(mainly illustrating variability in B_1 fold-style)



A. B_1 fold, south-east Olifantsberg

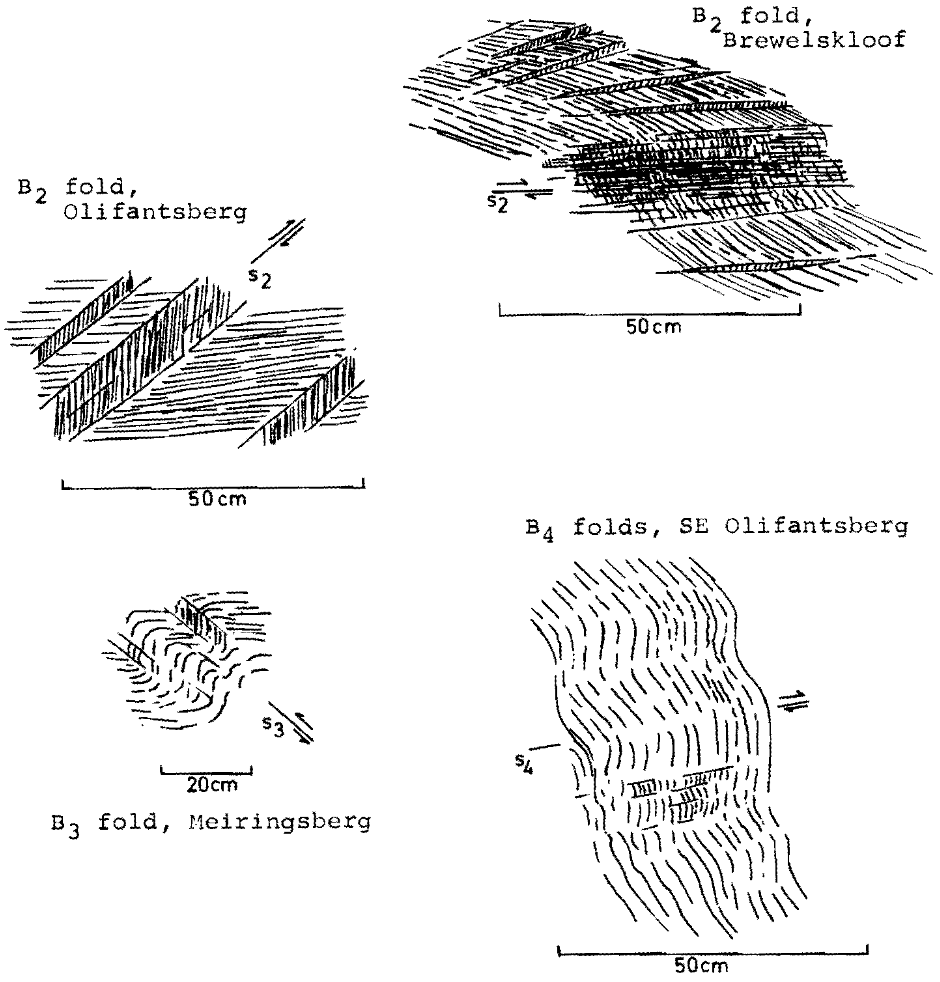
B. B_1 fold, Meiringsberg

C. B_1 fold, De Wet area

D. Mullion-like structure of disrupted bedding, northern Olifantsberg

FIGURE 4

Sketches of Late minor structures



B_2 fold, Brewelskloof

B_2 fold, Olifantsberg

B_4 folds, SE Olifantsberg

B_3 fold, Meiringsberg

There is one other point concerning B_1 folds. They are, in any case, rarely encountered; partly because of paucity of exposures, partly because of the monotonous and uniform lithology of the formations concerned. But intrafolial examples, in particular, are exceptionally difficult to trace, even where the character of s_1 and the orientation of l_1 suggests that they should be present. Perhaps this is because the structure in these parts is characterised more by extension and disruption of s_0 - giving rise to peculiar mullions - than by its compression and folding.

Late minor folds. The correspondence in style between small-scale B_2 structures and the Late major folds with which they are associated, is quite obvious and needs little demonstration. The folds are quite distinctive; they are generally asymmetric, and have sharp chevron profiles with short western limbs. In size they may range from centimetre-scale "kinks", with roughly axial-planar s_2 jointing, to larger flexures some metres in amplitude, with irregularly-developed s_2 crenulation foliation in their hinge areas. With these folds are probably to be grouped the B_3 structures which, in a very few places, show up as ill-developed conjugate partners to B_2 folds.

Late folds, whether with axial-plane s_2 or s_3, are well-developed only in those parts where s_1 is essentially coincident with s_0. Those parts in which s_0 and s_1 cut at any significant angle do not show any conspicuous effects of the Late folding, apart from some s_2 "jointing", along which some drag or kinking may have occurred.

B_4 minor folds have been observed as very open flexures or buckles which are generally small, en-echelon, and inconstant. They may occasionally have a slightly sharper form and be accompanied by slight axial-plane "shearing". The very sporadic and weak development of these folds indicates that they are probably the last to have formed in the tectonic history of these formations. Certainly no major structures belonging to this generation can be identified in the immediate vicinity. From the nature of the small folds, however, it seems likely that any such structure would be of a very great wavelength, similar perhaps to the regional late doming of subhorizontal schistosity near Moorreesburg (cf. Rabie, 1948), and not contained within the relatively narrow confines of the foreland outcrop.

b. Major tectonic structures

Because of the lithological character of the formations involved, the absence of reliable marker bands, and also the poor quality and limited extent of actual rock exposure, the major tectonic structures have largely to be inferred or reconstructed from the orientation data. The geometric analysis of large-scale structures at Worcester therefore rests heavily on the interpretation of fabric data from scattered outcrops.

This is a serious disadvantage which is further aggravated by the fact that, in these rocks, the dominant southerly-dipping s_1-fabric usually renders the detection and measurement of planar elements with other orientations difficult, if not impossible. Thus, in Fig. 5, where all the measurements of the principal planar fabric elements (s_0, s_1 and s_2) are plotted, the relative scarcity of northward dips in s_0 may be a reflection, not of the actual state of affairs, but rather of inadequate sampling.

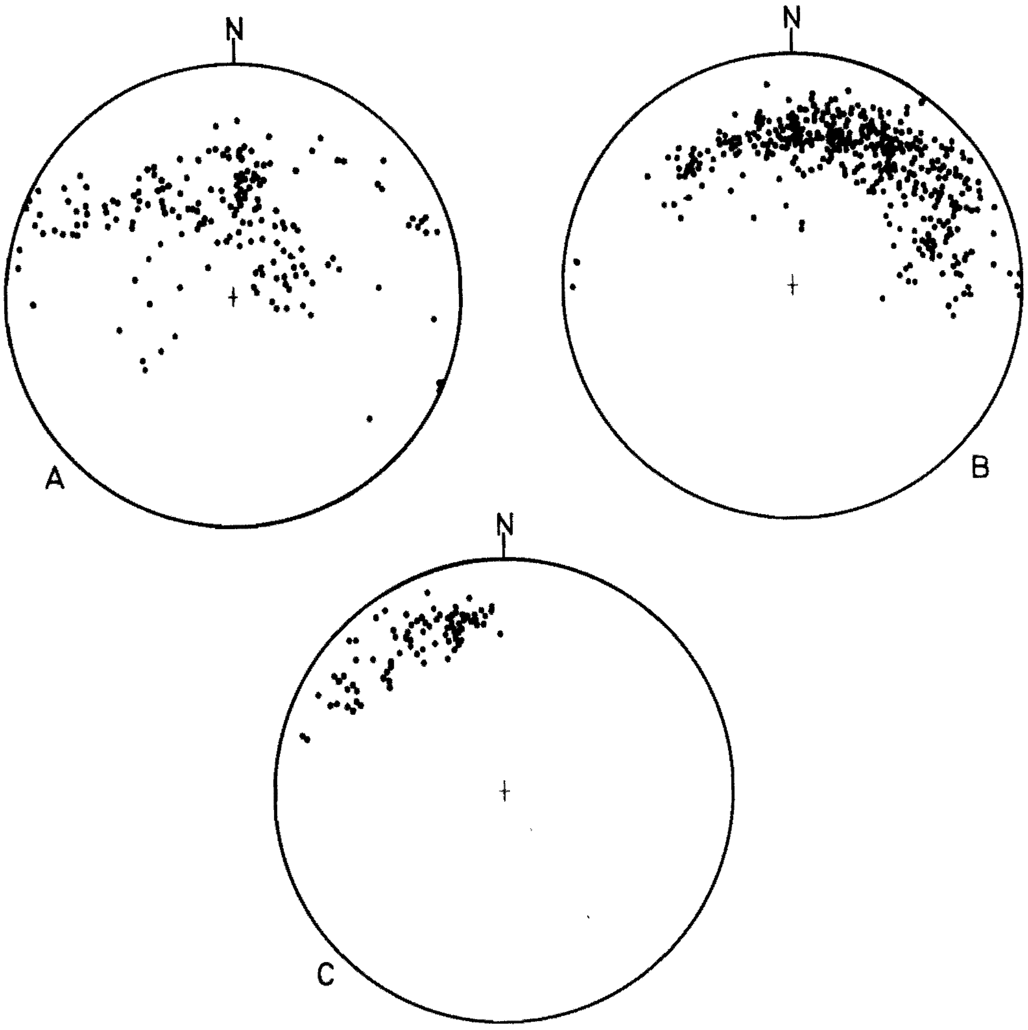


Figure 5. Planar fabric elements from the Brandwacht area (s_3 and s_4 excepted)

A. 182 poles to s_0
B. 405 poles to s_1
C. 71 poles to s_2

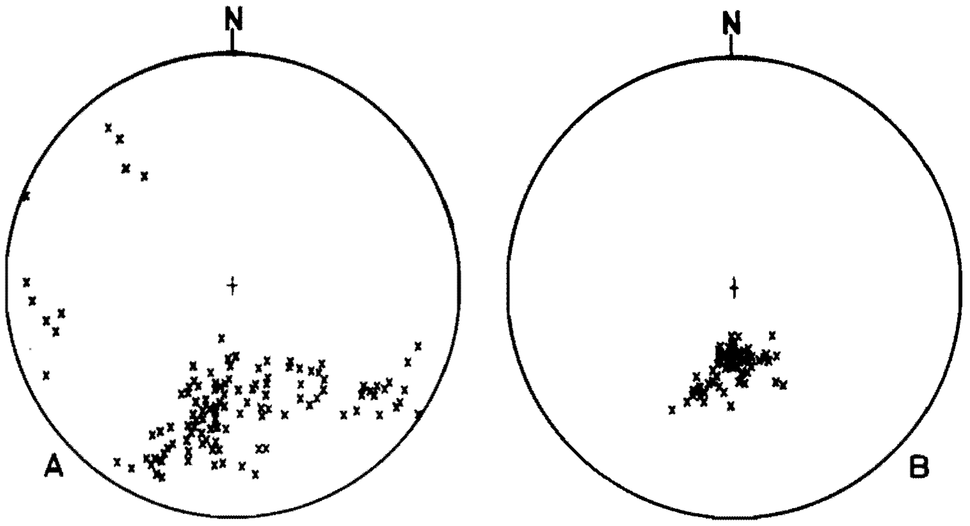


Figure 6. Linear fabric elements from the Brandwacht area (l_3 and l_4 excepted)

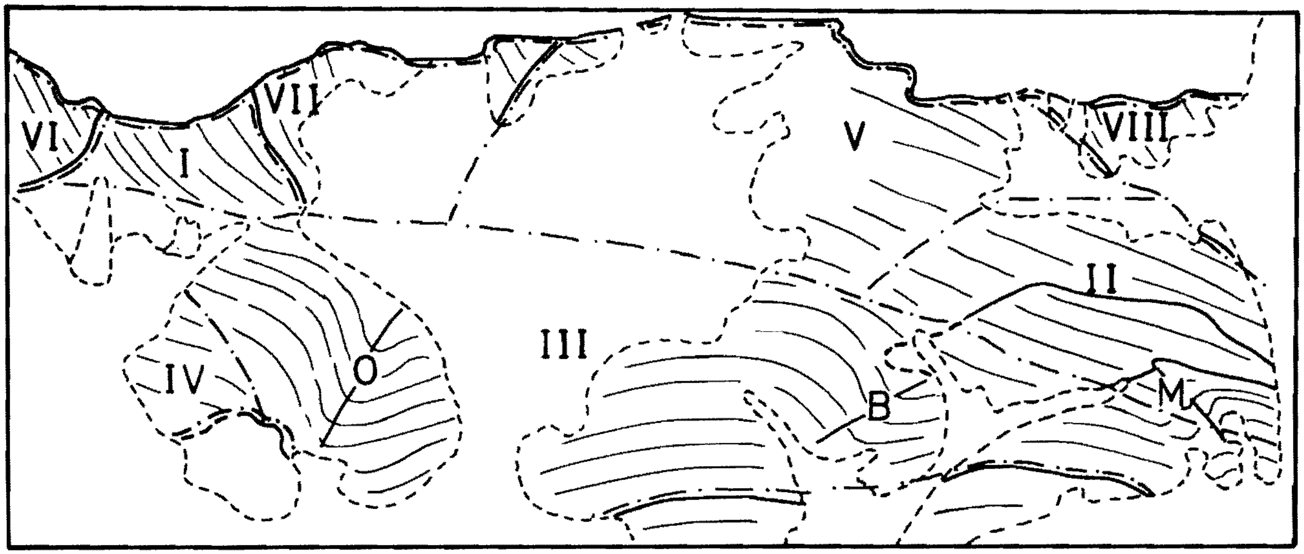
A. l_1: 119 fold axes and lineations
B. l_2: 59 fold axes and lineations

It is for this reason that no attempt at contouring fabric data to delineate orientation maxima has been made, for in the circumstances in which they have been collected, such an exercise would have little meaning.

The diagrams of Fig. 5 merely provide a qualitative base from which to begin the discussion of the larger structure of the pre-Cape rocks at Worcester. Of the three fabric elements represented (s_3 and s_4 are comparatively insignificant), s_2 shows the simplest distribution, with a rough monoclinic symmetry. The distribution of s_0 is plainly triclinic, and this is true, though less obviously so, for s_1 also. This, in short, means that it is not possible to discuss pre-Cape structure in terms of any one, simple, folding trend, nor is it possible to draw any single section to accurately represent the total structure.

This becomes more apparent in Fig. 6, in which all the data for the principal linear structures, l_1 and l_2, are represented. The Late linear structure, though tending towards an axial distribution, shows a definite monoclinic symmetry, while the fabric symmetry of the Early linear structure is obviously triclinic. In both cases the linear fabrics have a dominant southerly trend, which gives the impression that, on the whole, both Early and Late folds trend at right angles to the mean strike of the

FIGURE 7



SKETCH MAP OF BRANDWACHT AREA

Showing approximate boundaries of Subareas I - VIII and generalised structural form lines on the regional foliation, s_1.

The axial-plane traces of the Late major folds are also marked

O = Olifantsberg fold
B = Brewelskloof fold
M = Meiringsberg fold

main foliation. The impression is partly valid in the case of the Late structures, but as far as the Early folds are concerned, the position is as Fig. 6A suggests, very much more complicated.

The geometrical complexity of the early structures in particular makes it necessary to divide up the area between the Jan Dutoits and Hex Rivers into eight subareas (Fig. 7), five of which cover the Brandwacht Formation (I-V), while the remaining three cover the small and very poorly-exposed areas underlain by the phyllites and wackes of the Waaihoek (VI, VII) and Glen Heatlie (VIII) formations. This division into subareas is merely a rough breaking-down of the terrain into units that can be described conveniently. It is not strictly based on the criterion of homogeneity with respect to any particular fabric element (Turner and Weiss, 1963), but it does bear a certain relation to the nature of the Early structures.

The Late major structures do not really enter into this division of the terrain for they are mainly confined to one subarea, Subarea III, and as Fig. 8 indicates, are comparatively simple structures. It is obviously more convenient, then, to commence with the description of those major structures which have developed latest, and to proceed to the description of structures that have developed at successively earlier stages.

It is primarily with the structure of the Brandwacht Formation that this section deals, although the relationship between Subareas I (Brandwacht Formation) and VI (Waaihoek Formation) in the north-west part of the area deserves special attention as well.

(i) Late major structures : Large folds of an obviously late generation are to be found in the Brandwacht Formation in the southern part of the area. One of these, the largest and most conspicuous, occurs in the Olifantsberg foothills north of Chavonnes; another, which has a similar orientation to the first but is smaller, is situated near the National Botanical Gardens at Brewelskloof; and a third, which has a different general orientation and is also of no very great size, is to be seen in the Meiringsberg area near De Wet. The fabric elements which are associated with the development of these structures are s_2 and s_3; the former is roughly axial-planar to the first two structures mentioned, and the latter is the axial-plane structure related to the last-mentioned. Of the three major structures, the Brewelskloof fold is the one which shows the best development of an s-structure younger than s_1; it is really only in this fold, and then only in certain parts of the structure, that s_2 can be described as penetrative.

Minor folds of "kink-band" aspect are the most characteristic feature of the central zones of these structures and, in fact, the Brewelskloof and Meiringsberg structures themselves are perhaps best described as very large-scale "kink" structures in the s_1 foliation. Only the Olifantsberg fold can properly be described as an antiform. The other two structures, which may be parts of a single conjugate-fold structure, resemble small, sharp antiforms separated from each other, and from the Olifantsberg fold, by long, gentle synforms.

As the diagrams for the Late major structures indicate (Fig. 8), the individual structures are more or less cylindroidal. The Olifantsberg antiform (Fig. 8A) has an axial-plane which strikes and dips at about 030/80SE and an axis with trend and

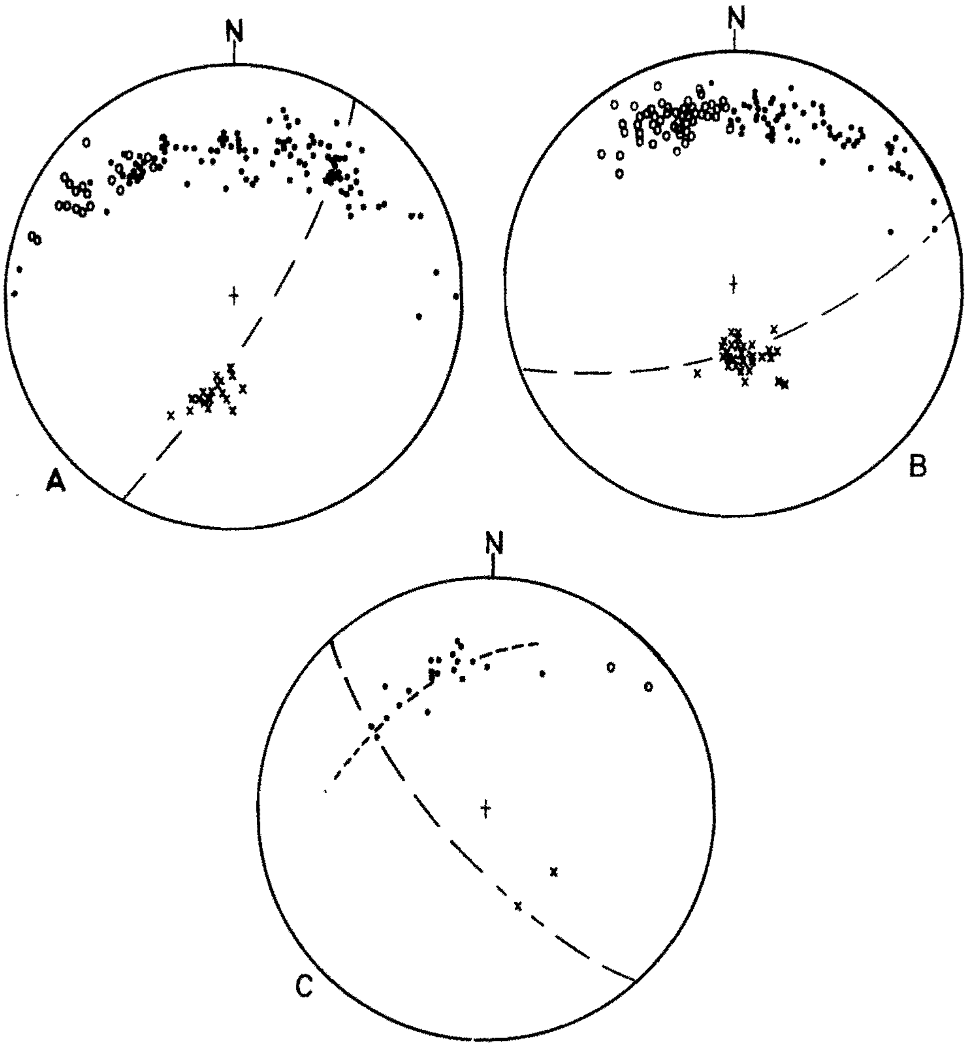


Figure 8. Structural geometry of the
Late major structures

A. The Olifantsberg fold (West)
B. The Brewelskloof fold (Central)
C. The Meiringsberg fold (East)

Dots = s_1 Circles = s_2 Crosses = l_2

plunge of about 195/55. The Brewelskloof structure (Fig. 8B) has a somewhat different orientation; its axial-plane strikes and dips at about 070/65SE and the fold-axis plunges due south at about 180/65. This, then, is quite clearly a neutral or reclined structure, (Turner and Weiss, 1963, p. 119; Fleuty, 1964a), having an axial pitch of practically 90°. The Olifantsberg fold, on the other hand, has an axial pitch of just less than 60°, and may be described as a virtually upright antiformal structure with a moderate to steep plunge. The axial-plane of the Meiringsberg structure (Fig. 8C) strikes and dips at roughly 140/75SW, and the fold has an axial trend and plunge of about 160/55.

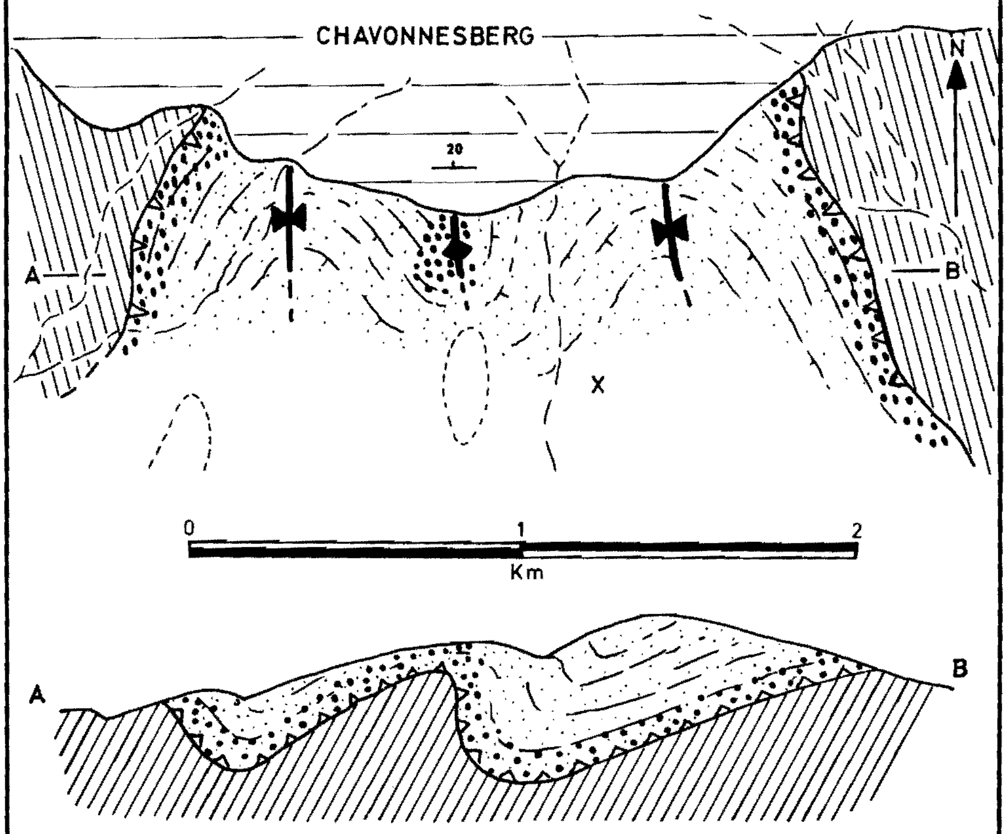
The first two Late major structures are particularly interesting in that they appear to represent, on a relatively smaller scale, the so-called pre-Cape fold syntaxis - the junction of N-S and E-W fold trends in the "Malmesbury" formations. Moreover, they appear to demonstrate that the "syntaxis" is not the result of the crossing at right angles of orogenic trends of different ages, but rather that it takes the form of a gradual swing of the Early structures, complicated by occasional sharp Late flexures. In actual fact, the explanation of this larger feature is probably not as simple as either view suggests, for the position, setting and significance of the Late major structures cannot be understood without a full appreciation of the nature of the Early folding in the pre-Cape formations.

(ii) Early major structures : At the base of Chavonnesberg, in the north-west part of the area under consideration, s_0 is remarkably well-preserved in the exposures of Brandwacht Formation immediately below the Table Mountain Group quartzitic sandstones, and it has here proved possible to unravel in some detail the geometry of this s-surface. In addition, the rather restricted belt of good exposure below the Table Mountain sandstone runs roughly east-west and accordingly cuts almost directly across the Early major fold structures here. This is particularly fortunate because it enables the relationship of the Brandwacht Formation to the adjacent Waaihoek Formation to be established with some certainty.

On Sheet 3319C (de Villiers et al., 1964) the Glen Heatlie and Brandwacht Formations are called "Malmesbury" and are said to be overlain unconformably in the west by the "Klipheuwel Formation". Thus on the east and west of the Chavonnesberg slopes, where the Brandwacht Formation greywackes are separated from the phyllites by coarse, irregular conglomerates (see Fig. 9), "Malmesbury-Klipheuwel" contacts were mapped. While, on this interpretation, it was accepted that the conglomerate on the east was to be included with the "Malmesbury" greywackes, the western conglomerate was designated as the basal horizon of the "Klipheuwel" and was said to rest, with a steep westward dip, unconformably upon the greywackes. The juxtaposition of conglomeratic greywacke and phyllite on the east was explained by postulating the existence of a reverse or thrust fault here.

However, a detailed examination of the so-called unconformity reveals the following features: the attitude of s_1, averaging 165/55SW, is the same in the phyllitic formations as in the greywackes, and the principal plane of parting in the conglomerates is the same; s_0, when traced from the greywackes into the conglomeratic zone, shows a regular change from gentle westerly to steep easterly dip about a large

FIGURE 9



MAP AND SECTION OF EARLY MAJOR FOLD STRUCTURES
BELOW CHAVONNESBERG
(SUBAREA I)

▨	Greywacke Conglomerate	BRANDWACHT FORMATION
▨	Slate and Phyllite	WAAIHOEK FORMATION

synformal structure; though s_0 in the conglomerates is generally effectively masked by s_1, occasional pebble-free bands may be observed to dip to the east; and the contact between phyllites and conglomerate, rather poorly exposed close to the stream bed, likewise shows an easterly dip. These observations indicate that the controversial conglomerate forms the western limb of a synform in the Brandwacht Formation of which it is essentially a part. The same conglomerate re-appears in the crestal region of an obvious antiform some distance to the east. Still farther in the same direction, on the slopes overlooking Brandwacht Valley, it dips gently westward beneath a large greywacke synform. The conglomeratic band separating the Brandwacht Formation from the underlying formations here, as elsewhere in the foreland outcrops, appears as a fairly constant marker.

The general structure of the Brandwacht Formation in Subarea I, then, is that of a large double synform resting upon the more slaty rocks of the Waaihoek Formation (Section in Fig. 9). The major structures in s_0 here have axial-planes which strike and dip at about 165/55SW, and axes which trend and plunge at about 190/30; the folds are therefore overturned towards the ENE. The synforms are characterised by steeply-dipping, and even slightly-inverted, western limbs and rather gently-dipping eastern limbs. Although a SSW axial trend for these Early structures may at first sound extraordinary, for "Malmesbury" structure is generally conceived as running NW-SE and perhaps even more E-W in these parts, the folds cannot be described as reclined. They have, as Fig. 10 shows, a moderate axial pitch of about 40°, and their apparent "cross-fold" orientation is given by a combination of this pitch with moderately- to steeply-dipping axial-planes which tend to strike more N-S in this particular subarea.

These geometrical relationships are obtained from Fig. 10A, in which are plotted s_0, s_1 and l_1 from all but one of the data stations in Subarea I. This apparently "anomalous" station (shown as point X in Fig. 9) lies below and away from the main strip of exposure from which the bulk of the data was collected. Here s_0 has a mean orientation of 085/56S and s_1, of 120/78SW; mean l_1 is 140/49 and s_0 is 129/45 (Fig. 10B). *

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* Notes: (i) These results were obtained by means of a computer program drawn up in MAC for an ICT 1300 series machine by the writer, and based on the material given in Ramsay (1967, p. 14-22). Mean data orientations are obtained by a vector-mean computation, β-axes by a least-squares method, and κ-axes (Tischer, 1962) by simply removing the "assumption of cylindricity" (Kelley, 1968, p. 225) from the β computation.

(ii) The actual angular difference between l_1 and βs_0 is only 8° (despite the impression of greater difference given by the data in trend/plunge form). This is remarkable in view of the clustered distribution of the few s_0 readings from which βs_0 was computed.

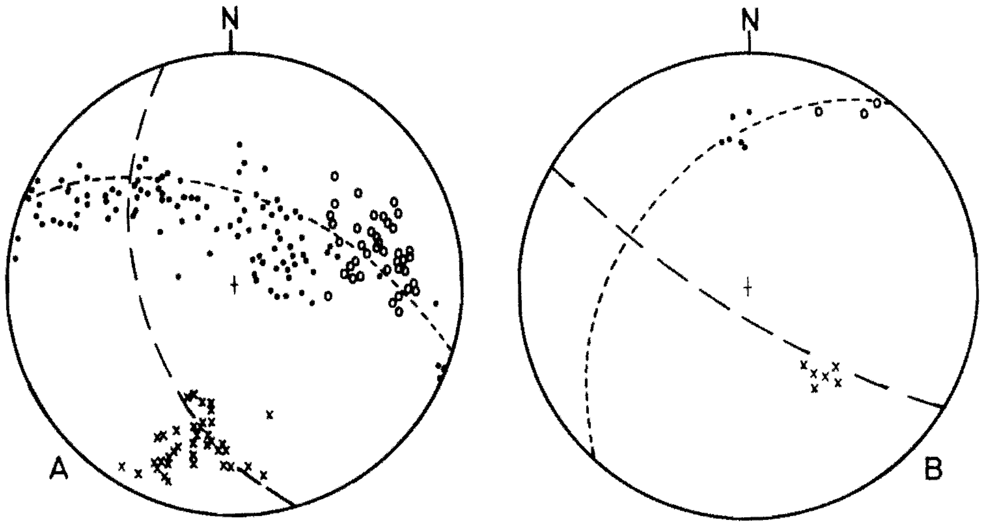


Figure 10. Structural geometry of the Chavonnesberg folds (Subarea I)

A. Data from the main sub-unconformity outcrop
B. Data from Station X in Fig. 9

Dots = s_0 Circles = s_1 Crosses = l_1

The attitudes of axial-plane foliation and Early fold axis at this outcrop are therefore quite different from those in the rest of Subarea I. But even in the latter parts s_1 is not very constant, and the great-circle about βs_1 (computed as 263/55 for this subarea) - on which the "anomalous" data almost fall - accounts for a good deal of this "spread". If the "anomalous" s_1 is rotated about βs_1 to the mean s_1 orientation for Subarea I, then l_1 - which undergoes an equal small-circle rotation about the same axis - comes to lie very close to the mean l_1 and βs_0 for the Subarea (about 190/30). This seems to confirm that βs_1 represents an axis of late folding about which all Early fabric elements, principally s_1, were slightly flexed. This later deformation may belong to the same generation of structures described in the previous section although its axial direction is different, but it is more likely to be a local effect of post-Cape movements, noticeable only very close to the Cape System unconformity.

Fig. 11A shows the best least-squares fit to all Subarea I s_0 data; the general best-fitting surface is markedly conical (axis 256/69: cone semi-angle 48°), though when constrained to define the best cylindrical surface, the computer yields a very acceptable solution (axis 201/31). The effects of the later deformation mentioned

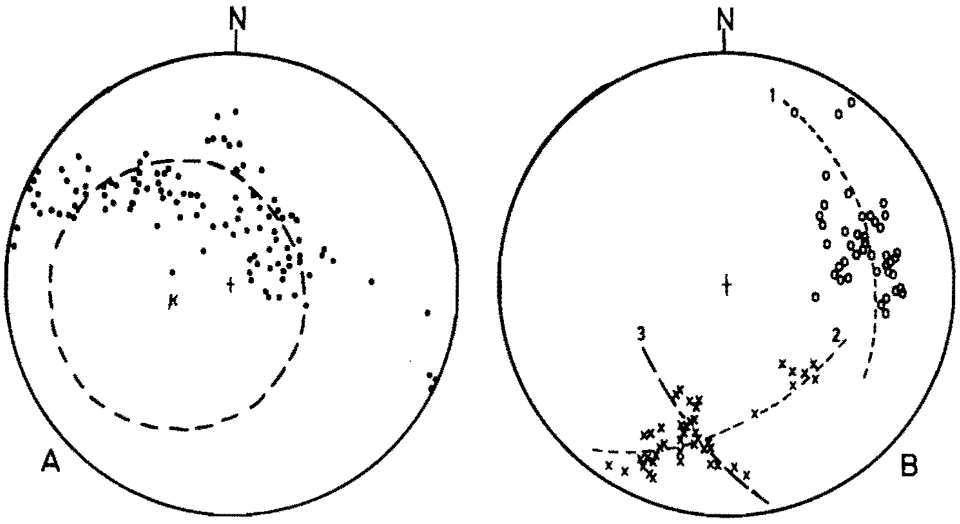


Figure 11. Structural geometry of the Chavonnesberg folds (Subarea I)

A. 110 poles to s_0 with best general least-squares fit to distribution (κ marks the axis of the cone)

B. 43 poles to s_1 and 44 l_1 lineations with partial girdles for:-

1. Plane of preferred orientation of s_1 poles
2. Plane of preferred orientation of l_1
3. Plane of mean s_1

above may have been instrumental in producing this apparent lack of overall cylindricity of the B_1 folds, but that this may not be the complete explanation is indicated by one other feature of the fabric data; namely, the tendency for part of the l_1 data to fall along a significant length of arc of the plane representing the mean s_1 orientation (Fig. 11B).

The coincidence may not be significant, but it does tend to suggest that l_1 had a variable orientation in the plane of s_1 prior to any deformation which affected them together. Although this angular dispersion of l_1 in the plane of s_1 appears to be as much as 40°, it is quite overshadowed by the effect of the slight later flexuring, and could even be dismissed as being due to measurement error, poor outcrop conditions, and so on - were it not that it reproduces, in a small way, the major feature of the Early deformation in these parts. Considered on a large scale, non-cylindroidal B_1 folds may thus be a primary feature of the Early deformation.

The primary variation of l_1 in Subarea I is scarcely noticeable apart from careful treatment of the fabric data. Far more obvious, however, is the considerable l_1 divergence revealed when the fabric diagrams for Subarea I are compared with that for the adjacent Subarea VI (Fig. 12). As already noted, s_1 has essentially the

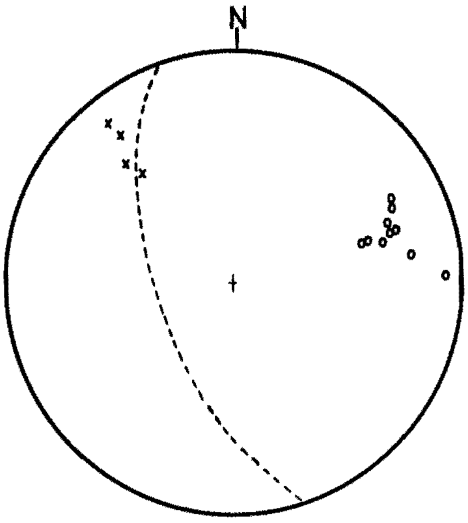


Figure 12. Structural geometry of Subarea VI

9 poles to s_1 (circles) and 4 l_1 readings (crosses) with mean s_1 plane indicated

same attitude in both subareas, but whereas the mean l_1 orientation in Subarea I is about 190/30, in Subarea VI it is roughly 320/30, i.e. north-westerly plunging. The Waaihoek formation in Subarea VI is very poorly exposed, and this observation is based on rather scanty data. But l_1 in the phyllite outcrops immediately west of Subarea I, though faint, can with reasonable certainty be said to be an s_1 /s_0 intersection lineation; it is oblique to a steeply-pitching and scarcely visible "grain" in the cleavage plane which presumably corresponds to the X strain axis in these slaty rocks.

The jump from southerly-plunging l_1 in the Brandwacht Formation to north-westerly-plunging l_1 in the Waaihoek Formation appears to take place suddenly across the contact, and not to be a continuation of the l_1 variation already noted for Subarea I. It therefore seems that some form of unconformity or discontinuity between the Waaihoek and Brandwacht Formations nevertheless exists, although the structural sequence established in this project is the reverse of that postulated by de Villiers, Jansen and Mulder (1964).

Subarea I is the only part in which large B_1 folds have been observed, or rather, in which a satisfactory synthesis of B_1 major structures has proved possible.

Elsewhere in the Brandwacht Formation it seems that such structures are either completely masked by the strong development of s_1 in a uniform lithology, obscured by poor exposure, or - for some reason - simply do not exist.

In Subarea II, the original bedding s_0 is reasonably well- preserved, but major B_1 folds were not seen, and it seems probable that they were never developed. This may be partly due to the presence of a massive body of basic "greenstone", the "biotite-eucrite" of de Villiers et al. (1964, p. 21) in this subarea, which was clearly emplaced prior to the deformation which produced the B_1 folds. The few poles representing dips in the NE quadrant (Fig. 13A) come from readings taken on minor B_1 structures. There appear to be no extensive areas of northward-dipping s_0 in Subarea II. Most s_0-poles tend to cluster about a point representing a strike and dip of about 090/35S.

Foliation s_1, while showing some degree of scatter, is reasonably consistent in orientation; it tends to strike and dip at about 100/55SW, and appears mesoscopically to have been little affected by later deformation over most of the subarea (Fig. 13B). All the more remarkable, therefore, is the considerable variability in orientation displayed by l_1 in the same domain. Most of the l_1-poles in Fig. 13B represent s_0/s_1 intersection lineations while some are the direct measurements of axes of small Early folds. Taking into account the scatter of s_1-poles, the correspondence between the near-complete girdle formed by the l_1 data and the trace of a plane representing the rough mean orientation of s_1 is fairly good.

Fig. 13B represents data gathered from outcrops scattered over a wide area, and it is possible that, within this subarea, still smaller domains more homogeneous with respect to l_1 could be defined. For instance, it appears that the orientation of l_1 may vary systematically from steep SSE plunges in the west to subhorizontal SE trends in the eastern part of the subarea. Even in the latter localities, where the dominant l_1 orientation is generally constant at about 125/10, a considerable degree of variation can be reproduced at a rather small scale. In Fig. 13C for example, s_0, s_1 and l_1 are presented for three minor folds occurring within about 50 yards of each other in the exposure near the gate of the farm Orange Grove, at De Wet. Each of these structures is a roughly cylindroidal fold in s_0 that has s_1 as its axial-plane, but the respective axial orientations in the uniformly-oriented s_1 are 125/13, 140/30 and 162/40 - a maximum axial divergence of almost 60° in the axial-plane.

This variation of l_1 in the plane of s_1 is the same feature which was noted for Subarea I, but there it is hardly as obvious or as large as in Subarea II. The phenomenon is taken to indicate that s_1 cuts through previously-folded s_0. The orientation of the resulting intersection lineation will change most rapidly at and about the trace of the hinge surface of the earlier folds, while on the planar limbs of the first structures, it will maintain a relatively constant attitude (cf. Elliott, 1968, p. 177). The greater degree of variation of l_1 in Subarea II, particularly in the south-east part, probably reflects such a higher rate of change, and indicates that the subarea contains or is close to the first-fold hinge line or lines.

Large, roughly cylindroidal second folds, like those of Subarea I, are therefore not to be expected here. In this respect, Weiss (1959b, p. 98) has noted that the "general rule .... with respect to the scale of successive generations of folds is that

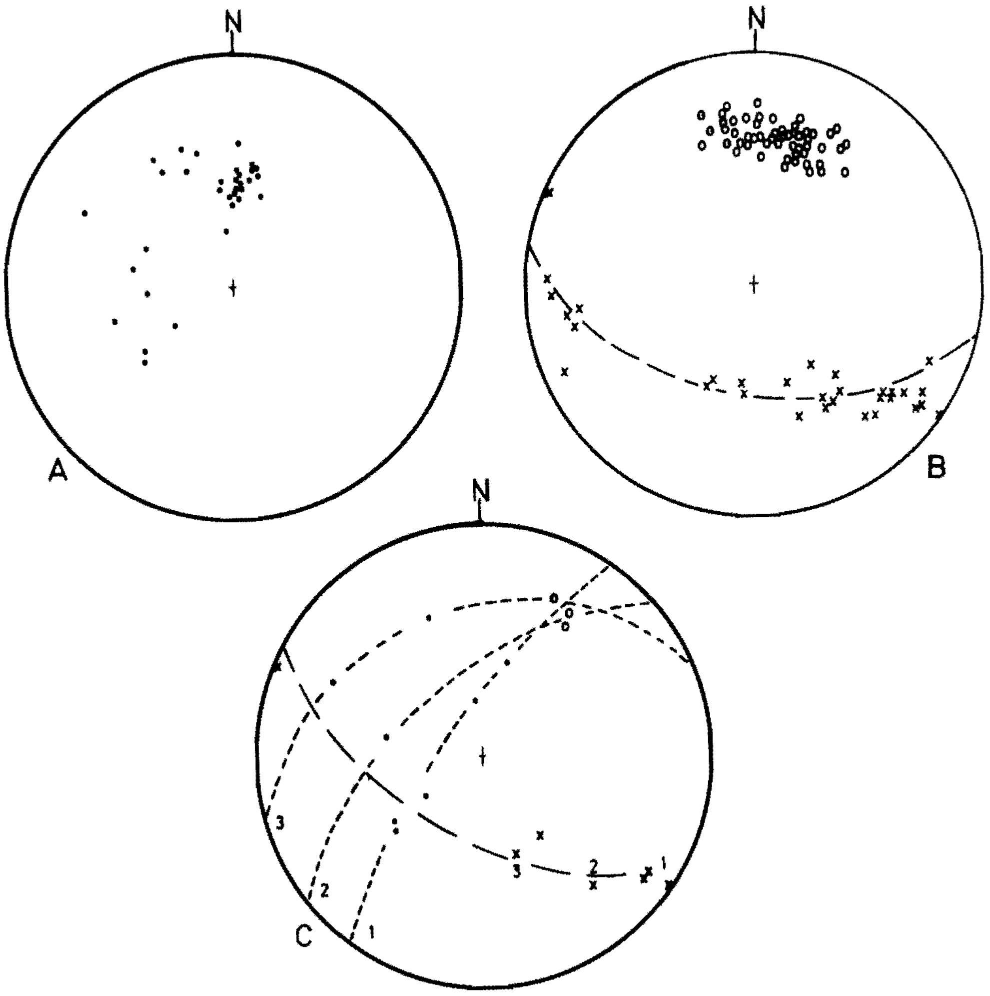


Figure 13. Structural geometry of Subarea II

A. Poles to s_0
B. s_1-poles and l_1, with mean s_1-plane indicated
C. Geometry of three minor folds in extreme east of Subarea II

Dots = s_0 Circles = s_1 Crosses = l_1

the largest folds of the second generation, where cylindroidal, must be smaller than those of the first generation, because they can be formed only on planar limbs of the first generation... ". To this must be added the observation that, generally, second folds will form only on suitably-oriented planar limbs of the first folds. For example, (Ramsay, 1963a, p. 381) ascribes the relative scarcity of large- and small-scale second folds in the formations of the Barberton Mountain Land to the "steep inclination of the strata before the second regional deformation... ".

A similar explanation may be invoked at Worcester to account for the absence of B_1 major folds in Subarea III. In this subarea s_0 is not generally seen, except as rare, disrupted remnants or folds of more competent greywacke floating in a finely-foliated "matrix" of phyllitic metagreywacke. In such cases the angle between s_0 and s_1 is usually very slight. Subarea III, then, is that part of the Brandwacht Formation in which s_0 has been extensively transposed into the plane of s_1. The main foliation is, of course, variously affected by the Late deformations, and all of the s_1, s_2, s_3, l_1 and l_2 data from this very large subarea have already been presented in Fig. 8. Fig. 14A represents the remaining fabric elements, namely s_0 and l_1. It will be seen that, despite the great variation in s_1 orientation produced by the Late deformation, l_1 maintains a fairly consistent attitude, primarily because l_2 - corresponding the axis of the main, B_2 folding in these parts - virtually coincides with the Early lineation.

As far as the Brandwacht Formation is concerned, only Subareas IV and V, both poorly exposed and yielding little information, remain. A few measurements of bedding from outcrops in which it can be recognised indicate that the general structure of Subarea IV may be similar to that of the eastern part of Subarea II; s_1 strikes and dips at about 110/50 SW and l_1 plunges gently to the SE or ESE; the constructed axis of folding, βs_0, plunges to the south-east at about 120/15 (Fig. 14B). On the maps Subarea V shows up as a large, open synformal structure comparable in its position and general form to the structures of Subarea I; in detail it may be even more complex than the latter.

Subareas VI, VII and VIII cover the Waaihoek and Glen Heatlie Formations which, in the north, underlie the Brandwacht Formation greywackes. These subareas are small and their state of exposure is extremely poor. The apparent structure of Subarea VI, in the west, has already been described - with emphasis on its differences from the adjacent Subarea I - and a diagram of the sparse observations from this part has been presented (Fig. 12). In Subareas VII and VIII the generally slaty rocks show only the principal cleavage, s_1 (Fig. 14C). The strike of s_1 varies from WNW to NNW (with the latter strike generally more prevalent closer to the T.M.S. contact), and it is not known whether this is a primary feature of the Early folding, or (perhaps more likely) a very late deformation such as that described from Subarea I.

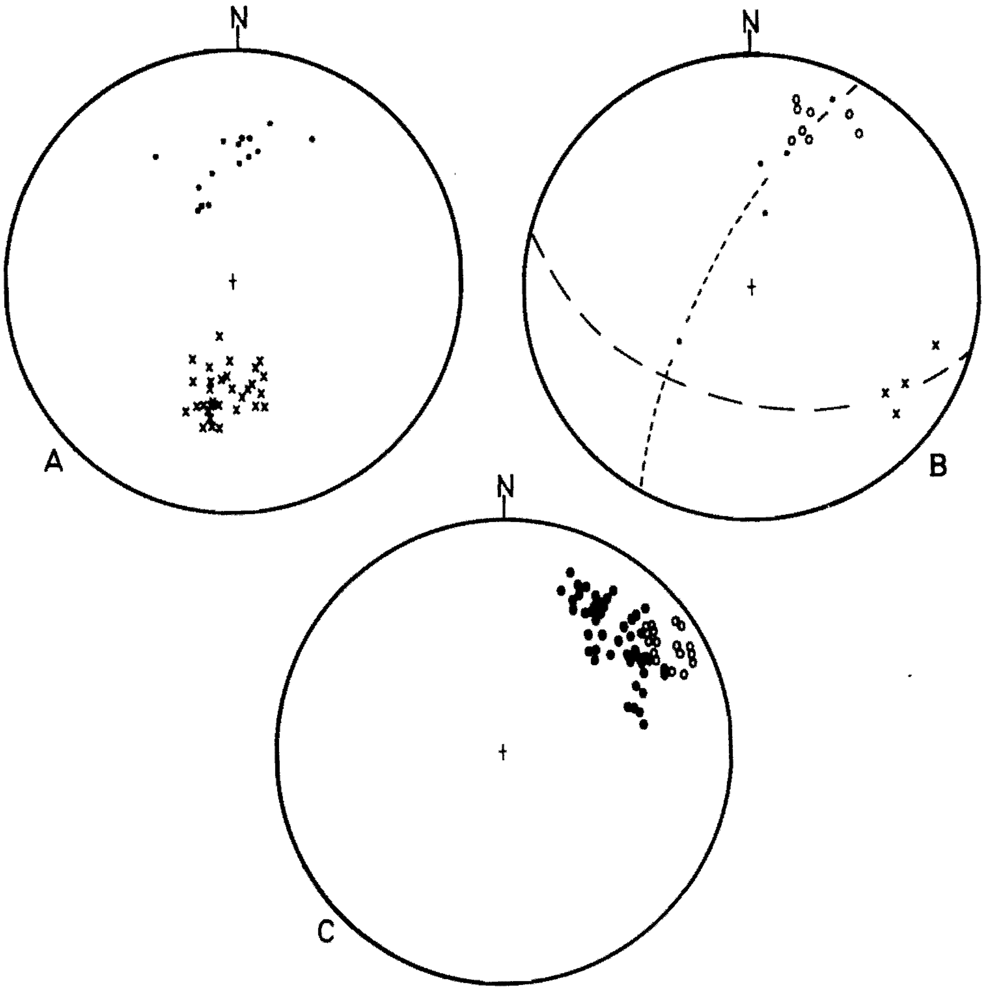


Figure 14. Structural geometry of remaining subareas

- A. Subarea III: poles to s_1 and l_1 intersection and stretching lineations
- B. Subarea IV: s_0 (dots), s_1 (circles) and l_1 (crosses) data
- C. Data for s_1 from Subareas VII (open circles) and VIII (closed circles); Waaihoek and Glen Heatlie Formations respectively

3. Faults and Slides

The previous map (de Villiers, Jansen and Mulder, 1964) shows three faults in the pre-Cape rocks of this area:-

(i) A reverse fault in the north-west, separating the so-called "Klipheuwel" (Waaihoek Formation) from the "Malmesbury" (Brandwacht Formation) appears to fall away with the premises on which its existence was based. However, some form of discontinuity between these formations can be inferred from the structural geometry across the western limb of the synformal Chavonnesberg fold complex, and it seems likely that the "reverse fault" contact may yet form part of a much larger plane of tectonic dislocation.

(ii) The fault, shown as running up to Spitskop in the south-east, corresponds, in part at least, to the small Meiringsberg fold structure. Any actual dislocation which may have taken place parallel to the axial-plane of the structure is not very appreciable.

(iii) The major reverse fault shown as running E-W across the area is represented in the east by a mylonitic or phyllonite band coplanar with s_1 in the rocks of the Brandwacht Formation. This zone of concentrated movement appears to have come into existence while s_1 was being formed. There is however, no clue to the magnitude of movement. The present mapping indicates that, in its westerly extension, this thrust runs farther south towards the Olifantsberg fold, rather than towards the nek separating Chavonnesberg from the Olifantsberg foothills.

The present mapping also indicates the existence of two further, and more important, tectonic discontinuities in the area. The first, and earlier, has already been alluded to in (i) above, and in the discussion of relationships between Subareas I and VI. The writer believes that this discontinuity at the base of the Brandwacht Formation is a slide. This term, which was coined by Bailey (1910) as a synonym for "fold-fault", has been more precisely defined by Fleuty (1964b, p. 454) as: "... a fault formed in close connection with folding, which is broadly conformable with a major geometric feature (either a fold limb or axial surface) of the structure, and which is accompanied by thinning and/or excision of members of the rock succession affected by the folding...". As used here, it has a somewhat looser sense, indicates that the Brandwacht Formation is allochthonous, and that the earliest fold or folds in the greywackes were formed during its translation.

The second major tectonic discontinuity in the area, the fault which has brought granitic rocks into contact with the Brandwacht Formation, is probably broadly related to the structure described in (iii) above. Both structures appear to be closely connected with the main phase of folding and deformation in the surrounding rocks, but while the slide definition given above may cover their description also, they correspond more to the classic thrust concept.

Though Rastall (1911, p. 710) believed that the "phyllite-gneiss" (the term originally applied to the granitoid rocks by Rogers and Schwarz, 1898) represents "masses of granite or granite porphyry which have been intruded into the sediments at some period prior to the final foliation", and claimed to found conclusive evidence for an intrusive origin, his hypothesis appears to be untenable in the light of the present structural findings. The "parallel foliation" which he noted to have affected "both sediment and intrusion alike" (op. cit.) is s_1, the regional foliation in the pre-Cape terrain. In the granitic rocks, particularly near their contact with the metasediments, this foliation has produced strongly porphyroclastic and even mylonitic textures. To the writer, this indicates that the rocks in question have reached their present position as a result of extensive thrusting. They probably represent the basement upon which the pre-Cape formations were deposited.

It is perhaps no accident that, over quite a considerable portion of its length, the great Worcester Fault is associated with small patches of sheared granitic rocks situated just north of its outcrop trace. The approximate coincidence of the Worcester Fault with a belt of pre-Cape thrust masses tends to disguise the real significance of the latter.

4. Discussion of the Pre-Cape Tectonic Phases

A preliminary distinction, based on relationships to s_1, between Early and Late structures has already been made; this allowed the discussion of major structures to take a fairly convenient form. This discussion has shown, however, that there is more to the structural history of this terrain than the simple division into Early and Late structures conveys. The following section deals with the kinematic significance of the geometrical relationships and defines more explicitly the respective phases of pre-Cape deformation.

It has recently become common practice in many parts of the world, to name deformation sequences F_1, F_2, F_3 and so on. This terminology was introduced into the structural description of the Scottish Caledonides by Rast (1958), and has become quite well-established there and elsewhere. This practice may tend to impose an unnecessary rigidity, and hamper the subsequent incorporation of intermediate phases (Chadwick, 1968, p. 1125). In the pre-Cape, where very much more detailed work has to be done before the regional relationships of deformation phases are settled with any certainty, this is undesirable. Therefore, in order to avoid a possible source of future confusion, Chadwick's example has been followed, and arbitrary letters of the alphabet have been used to label tectonic events.

a. Early Phases

(i) Phase O : Because the regional foliation s_1 appears to be the first penetrative tectonic structure imprinted upon the primary sedimentary fabric of the formations, it may seem as if the movements which led to the development of this structure represent the first phase of deformation. Certain features of fabric and geometry, however, do not accord with this view; most of these have been mentioned in the sections dealing with minor and major structures, but it may be useful to summarise them together here:-

The variation in the physical character of s_1 from common varieties of axial-plane foliation to an intense, almost phyllonitic schistosity or "transposition" foliation, is a feature which does not easily escape notice. On a previous map (Univ. Stell., 1948), this phenomenon is recorded as a supposedly stratigraphical distinction between different parts of the Brandwacht Formation. On the present interpretation, the factor determining whether s_0 was folded and preserved or disrupted and destroyed by transposition, was mainly its orientation in earlier structures upon which s_1 was more or less discordantly superimposed.

The local and regional variability in orientation of B_1 fold axes, and Early linear structures in general, is probably the feature which most clearly points to the conclusion that the Early deformation is complex. This is obviously not due to their distortion by the Late tectonic phases.

The variation in style, amplitude and possibly also relative concentration of B_1 minor folds in different parts of the terrain is also significant in this respect. The originally variable orientation of s_0 with respect to the obliquely superimposed s_1 may be proposed as an explanation for these related features.

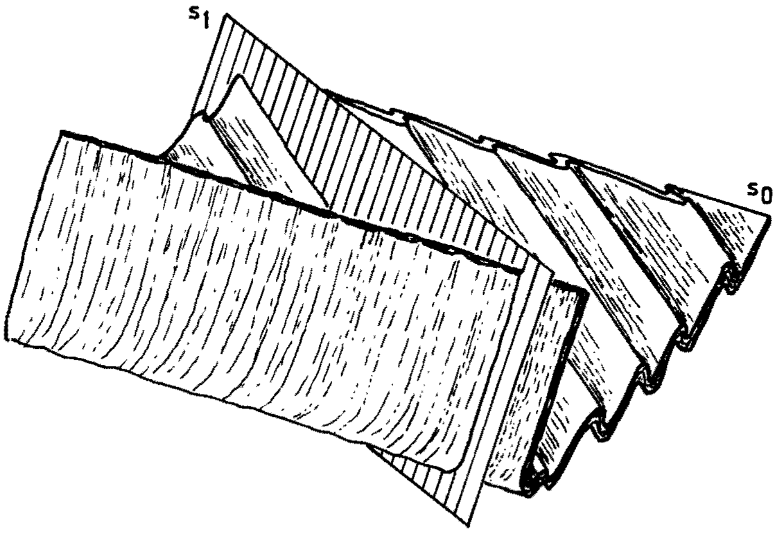
These are the main lines of evidence from the minor tectonic structures upon which the Phase O hypothesis is based. Unfortunately, no definite examples of Phase O minor folds have been seen in the field. As far as the macroscopic structure of the terrain is concerned, it is also unfortunate that there are no distinctive lithological markers in the greywacke sequence to allow large-scale Phase O folds - or lithostratigraphic patters resulting from the interference of this hypothetical phase with the main Phase M deformation - to be traced on the map. However, the size and distribution of Subareas I - V in the Brandwacht Formation appear to offer some indication of the geometry of a major Phase O structure.

Subareas I, II and V appear to represent the now distorted, but on average gently-dipping (10°- 20°S?) northern limb of a very large synform, while Subarea III forms the approximate locus of the originally more steeply-dipping (± 50° - 60°S?) southern limb. The axial-plane of this structure probably had a moderate to gentle dip to the SSW, and the fold presumably faced in a north-easterly direction. In the west, Subarea IV appears to fall south of this major structure, but in the east Subarea III terminates abruptly against the Phase M thrust or slide that has brought highly-sheared granitic rocks to rest above and against the Brandwacht Formation metagreywackes.

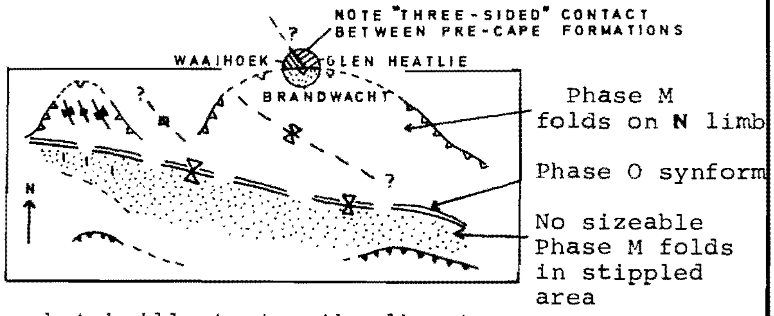
If this idea of the lithostructural differences between subarea being due to the superimposition of the main-phase structures upon a pre-existing fold is correct, then the fold thus indicated is of quite considerable size. The apparent lack of structures indicating penetrative internal strain during the Phase O folding is therefore remarkable. Even where Phase M structures are not very pronounced (and therefore where evidence of tectonic structures of an earlier phase might be expected), s_0 shows no obvious evidence of prior distortion. This feature may be significant in indicating the nature of the Phase O episode.

Ramsay (1963b, p. 387), for instance, describes the major cover-nappe structures in the Brianconnais zone of the Franch Alps as having been refolded by folds to which the main schistosity is axial-planar, the latter being itself locally cut by two independent sets of less penetrative, strain-slip foliations. The initial deformation which gave rise to most of the PreAlpine and Helvetic nappes of France and Switzerland left little or no penetrative trace on the internal structure of these masses, some of which have suffered horizontal displacement of the order of 50 Km. (cf. Ramsay, 1967, p.51). Only marginally, or where they have been refolded in later compressive

FIGURE 15



The upper sketch illustrates, very schematically, the geometrical relationships which are postulated to exist between s_0 and s_1 in the Brandwacht Formation. In the sketch, s_1 is not axial-planar to the fold in s_0. On the farther limb, relatively gently-plunging smaller folds, with s_1 as axial-plane, can form, but on the nearer limb the intersection of the two planes is such that no folds can form.



The lower sketch illustrates the direct application of the ideal model to the Brandwacht area.

phases, do the Alpine cover-nappes show the more obvious mesoscopic effects of strain. Broadly comparable phenomena have been described from most of the classic European fold belts.

The nappe interpretation of the large Phase O structure in the Brandwacht greywackes has the advantage of simultaneously explaining the presence of a tectonic discontinuity at the Base of the Brandwacht Formation, and its overlapping of lower formations of somewhat different facies. The concept of *recouvrement* - tectonic overlap - is, of course, the essence of classic nappe theory (Bertrand, 1884). The root of stratigraphical difficulties in the "Malmesbury" formations probably lies with the enigmatic Phase O folding, and the odd, "three-sided" nature (Read, 1948, p. 33) of some of the formational contacts farther east in the foreland outcrops of the Langeberge (cf. Univ. Stell., 1948) may be due to tectonic sliding during this phase.

(ii) *Phase M* : According to the concept just outlined, translation accompanied by large-scale parallel or concentric buckling of the strata, may have been the characteristic feature of the first phase of tectonism. The second episode, Phase M, on the other hand, was a phase of strong, regional compression which resulted in the imprinting of a very penetrative strain fabric on the rocks involved. Distortion was probably the principal component of Phase M strain.

In the field-work for this project, little attention was paid to the matter of finite strain as such, or to its measurement; the main emphasis here falling on structural geometry. Any complete treatment of Phase M must, however, take this very important aspect into account, especially as strain relationships can affect the geometry of early - or simultaneously-formed folds in a number of ways.

The most conspicuous structure belonging to this phase, namely s_1, has elsewhere in the pre-Cape terrain been given the genetic name of "flow cleavage" (de Jager, 1941) because of its apparent mechanical function as a surface of non-affine slip, shear or flow in the process of Phase M folding - on analogy with the so-called "card-pack" mechanism for producing similar folds. There can be little doubt that the actual mechanism of Phase M folding is more complicated than this, for the B_1 folds are certainly not ideal similar folds. The initial stages of development of these folds were probably governed by a buckling mechanism, the folds thus formed subsequently becoming more and more flattened normal to their axial-planes, and also modified by some shear parallel to the axial-planes, as the degree of strain in the rocks rose and the principal cleavage formed.

It seems likely that the amount of flattening of the Phase M folds may vary on a fairly large scale over the area, and also that the degree of stretching or elongation parallel to the principal axis (X) in the plane of the foliation shows systematic changes. In Subarea III, for instance, strain phenomena in the form of intensely-elongated pebbles, mineral lineation or striation in very schistose s_1, and so on, appear to be much more impressively developed than in some other parts of the Brandwacht Formation. The nature of three-dimensional Phase M strain (Flinn, 1962) may also vary between different volumes of the Brandwacht greywackes. Thus in Subarea III again the bulk strain may in places have been of a "constrictive" (strain ellipsoids with $k \to \infty$, *op. cit.*; also Ramsay, 1967, p. 136) rather than a "flattening" ($k \to 0$) character. This is indicated by the apparently "cigar-like" nature of some deformed inclusions. In addition, features of the Phase X deformation (to be described in the next section) suggest that towards the end of Phase M constriction was becoming more important in Subarea III, perhaps as a direct result of general flattening and sideways extension in other parts.

These possibilities of general strain inhomogeneity in the Brandwacht Formation raise some important problems in the interpretation of Phase M minor structure geometry. In the previous sections, attention has been drawn to features which are taken to indicate that Phase M has been superposed upon an earlier folding. However, on their own, these features can be explained by a pattern of inhomogeneous Phase M strain without the necessity for postulating a prior phase.

In an area of comparable metamorphic grade, Dewey (1967, p. 150) notes that : "Differential flattening normal to S_1 and differential stretching in S_1 produced slides and very variable fold plunges", and that " .. D_1 folds are internally rotated into downward-facing attitudes .. .. as a result of differential stretching". Similarly, Chadwick (1968) has demonstrated that the curvature of Alpine fold hinge-lines "... may be attributed to differential strain extensions along both strain directions contained within the plane of the Phase B (main) schistosity"(op. cit., p. 1130). In like manner, therefore, the B_1 fold-plunge variation at Worcester, and the geometric heterogeneity of the Early structures in general, may also not indicate the superposition of Phase M upon an earlier folding.

On the other hand, it seems reasonable to expect that a phase of folding prior, and slightly oblique, to the main Phase M compression may have affected the orientation and the shape of the Phase M strain ellipsoid in various ways. At Worcester there may be a real difficulty in deciding whether the pattern of strain is more cause or more effect of the complex Early fold geometry. For example, in Subarea III the steep pitch of the intersection lineation may be due to its having been rotated towards the direction of somewhat exceptional maximum stretching, but it is also possible that an already steeply-pitching linear fabric was merely one factor facilitating strong elongation in these parts. The author favours the latter possibility, namely that the Phase M strain pattern is a function of pre-existing geometrical complexity.

The purpose of pointing out the possible implications of differential or inhomogeneous strain is to indicate the limitations of a purely geometrical study of a structurally very complex terrain. However, as Elliott (1968, p. 189) notes: "...rigorous attention to geometry is not only essential for the determination of the stratigraphy of an area but is a necessary prerequisite to understanding the deformation history and measuring finite strain". Hopefully, the present work is a first step in the direction of future structural studies which will deal in greater detail, and if possible in a more quantitative manner, with aspects of both geometry and strain in the Early deformational history of the pre-Cape rocks.

b. Late Phases

As the late phases of deformation, which are quite well displayed by the folding of the main foliation have relatively little to do with the problems of pre-Cape stratography which were the original targets of this structural study, the following discussions will be confirmed to their most important aspects only.

(i) Phase X : The Phase X deformation is taken to include movements leading to the development of both s_2 and s_3. The broadly conjugate relationship of the major B_2 and B_3 folds is the main feature which suggests this grouping, but in addition, small, generally irregular, conjugate fold structures in s_1, have been seen in some places, though these are quite rare. Some of these fold pairs have an almost orthorhombic symmetry ($B_2 \wedge B_3 \rightarrow 0$), others such as those seen on the eastern limb of the Olifantsberg are monoclinic or even triclinic, with a fairly large divergence between B_2 and B_3 axial directions (Ramsay 1962). This suggests that the orientation of the principal stresses varies with respect to the foliation, though the form of the structures suggest that P_{max} generally lay in, or very near to the s_1 plane. On the large scale, the Phase X structures also depart from overall orthorhombic symmetry, for the eastward-facing Meiringsberg fold (B_3) plunges to the SE, while the westward-facing Brewelskloof and Olifantsberg folds (B_2) plunge more west of south.

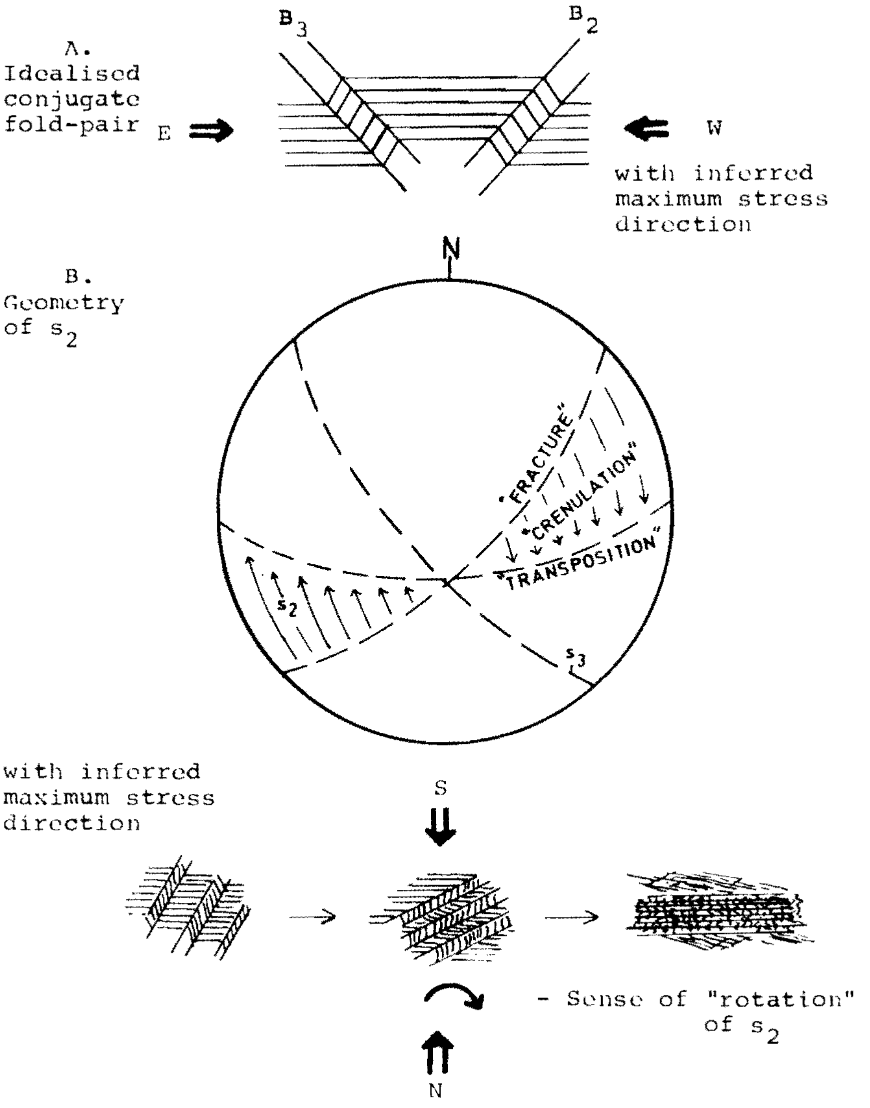
There is, however, some difficulty in reconciling the conjugate form of these major and minor structures, and the directions of Phase X maximum compressive stress derived therefrom, with some features of s_2 and its related minor folds. B_2 and s_2 structures are generally, and even in individual conjugate structures, very much better developed than B_3 and s_3. The variable development of s_2 has been described in the section dealing with minor tectonic structures, and it was noted there that s_2 showing features of an incipient stage of development, tends to strike more NNW, while s_2 showing features of strong development - being axial-planar to tight, almost symmetrical, small chevron folds and associated sinusoidal folding in occasional quartz-veins in s_1 - tends to strike almost E - W.

Late foliations such as s_2 are generally considered to rotate, with continuing strain and better development, until they are almost normal to the direction of maximum compressive stress by which they have been produced (Flinn 1962, p. 424); Turner and Weiss, 1963, p. 465; Roberts 1966 p. 848). If this is true also of the s_2 foliation at Worcester then the sense of rotation which s_2 displays indicates that the externally applied Phase X principal compression acted almost normal to the average unfolded attitude of s_1; that is, it acted along roughly NNE-SSW lines rather than along the WNW-ESE lines (parallel to average s_1 attitude) indicated by the small-scale conjugate structures and the broad configuration of the major folds.

The Worcester area does not appear to be unique in showing such puzzling late-phase stress-strain relationships. The "Late Crossfold" or F_2 structures of the Scottish Highlands, described by King and Rast (1955, 1956) and others, are direct analogues of the Phase X folds in the pre-Cape. King and Rast (1956, p. 191) record that the "strain-slip" associated with more open crumples of the early schistosity is highly inclined to the latter, whereas the "new axial-plane schistosity" into which the former passes with the development of more strongly recumbent cross-folds "lies more nearly coincident with the early schistosity as preserved in unfolded layers". They have concluded that : ".... the cross-folds are 'accommodation' structures resulting from confinement of the orogenic belt in the direction of the major b-axis" and that "... they arise from complementary stresses produced in the orogenic belt during deformation, and do not reflect the direction of forces applied externally in the development of the orogenic belt as a whole". (King and Rast, 1955, p. 265).

FIGURE 16

Schematically illustrating some features of the Phase X deformation



On a somewhat smaller scale, broadly conjugate structures of the Moine Thrust Belt (Johnson, 1956, 1957) show a similar stress-strain pattern. (Johnson, 1956, p. 253) echoes King and Rast in his explanation of these structures in terms of "complementary stresses", and in his assertion that "the folds do not reflect the direction of forces applied externally to the rock mass as a whole...". Sutton and Watson (1958, p. 248) express the same idea more directly; "As the rocks were rolled out, they may have tended to expand in the direction perpendicular to the thrust movements, and the pressure of this expansion found relief by predominantly upward movements in the conjugate folds and shears".

Although Johnson (1964, p. 466) regrets the impression which his earlier papers convey, that conjugate folds are special features of fault zones, it is perhaps no coincidence that the Phase X structures should occur in such close conjunction with an apparently tremendous thrust or slide which resulted in the superposition of sheared granitic rocks upon the Brandwacht greywackes. It is therefore interesting to note that the Meiringsberg and Brewelskloof structures appear to represent a local sideways escape of metasedimentary material away from a compressed zone in which the relatively rigid granitic thrust mass and the large basic intrusive in the formation approach each other closely.

In this kinematic picture, the Phase M and Phase X movements are very closely connected, with Phase X deformation occurring alongside and "balancing" as it were, further Phase M compression and flattening in other parts. This model however, does not quite account for the apparent reaction of the more penetrative variety of s_2 to the applied external (i.e. "Phase M") stress. A possible explanation of this phenomenon is suggested by Roberts' (1966, p. 851) idea that domains of penetrative secondary foliation have developed by a plastic strain mechanism after initial elastic buckling had overcome a yield threshold. It may, therefore, be suggested that, in the latest stages of Phase M compression, the subsidiary lateral stress, transmitted elastically along the Phase M schistosity locally produced the initial Phase X buckles which, having in places passed into the field of plastic deformation, responded further by flattening normal to the applied external confining pressure.

(ii) Phase K : Structures of this generation (s_4, l_4, and B_4) are rare and very little attention has been paid to them. They appear to be definitely later than Phase X. It is possible that they have been formed during the deformation of the overlying Cape and Karroo System rocks in the region, but this is a problem which must necessarily be settled over a much wider area of the Western Province.

c. Synopsis

One point that needs to be stressed in the discussion of the different phases of pre-Cape deformation is the essential unity of the sequence. It is important not to lose sight of this fact in the welter of detail about superposed folding in the rocks. As Elliott (1966, p. 171) notes, one of the results of modern structural analysis seems to be that a particular sequence of deformation episodes, present in areas of the Scottish Highlands and Western Alps for example, may well be typical of all mountain belts and metamorphic terrains: "Large folds, often as large as to be called nappes, are responsible for the repetition of units and the regional distribution of stratigraphy.... The early phase is overprinted by a phase of deformation with smaller folds which characteristically exhibit an intensely developed cleavage or schistosity parallel to the hinge surface... Still later deformation phases are much less intense and the folds are well-defined by the folded schistosity".

At Worcester, too, all of the different pre-Cape folding and deformation episodes appear to be the result of only one major tectonic, or orogenic episode. This has been called the "Malmesbury orogenetic cycle" (Scholtz, 1946) and more recently, the "Damaran Episode" (Clifford, 1967). The author believes that both terms are unsatisfactory; the former because of its stratigraphic associations (some of the many remaining difficulties with the pre-Cape stratigraphy will be outlined in the concluding section), the latter because of the need for a term of more local application which deals specifically with tectonic aspects of the pre-Cape rocks. The term "Saldanian Orogeny" or "Saldanian Tectonic Episode", which the writer presumes to coin, fills this role.

The rocks affected by the Saldanian Episode show quite widely differing structural features in different parts of the Western Province. In the Worcester district the epi-metamorphic terrain is characterised by a steep to moderately dipping slaty foliation upon which a number of later foliations have been superimposed. This picture also holds further east near Robertson, where De Jager (1941) has described five generations (s_1 - s_5) of pre-Cape cleavage. West of the Cape mountains, between Wellington and Piketberg, a simple steep to vertical cleavage in scarcely metamorphosed rocks shows slight trace of weak late deformation. The immediately adjacent area between Malmesbury and Moorreesburg presents an extreme contrast, for here the main foliation or schistosity in more meso-metamorphic rocks (the Swartland schists) is in general subhorizontal, shows folds of recumbent attitude and intrafolial style, and is itself folded into great dome-like structures many kilometres in wavelength; there are also a number of secondary cleavages developed here (cf. Rabie, 1948; Newton, 1966). Farther west, towards Cape Town, the Saldanian structures appear far more simple, but outcrops along the coast, near Blaauwberg for example, show complicated patterns of superposed deformation. Early recumbent folds are here refolded by the steeply-dipping main-phase folds and some late-phase features are also seen.

C. SUMMARY OF RESULTS

1. The epi-metamorphic pre-Cape rocks in the vicinity of Worcester can be broadly divided into three formations; Waaihoek, Glen Heatlie and Brandwacht.
2. These formations show at least four generations of minor tectonic structures, which can be divided into Early and Late categories, depending on their relationship to s_1, the main foliation or cleavage in the rocks.
3. From the point of view of stratigraphic reconstruction, only the Early structures are important. These, however, show a degree of geometrical variability which certainly cannot be ascribed to Late folding effects. Nevertheless, geometrical analysis in the relatively homogeneous Subarea I shows that the Brandwacht Formation rests upon the Waaihoek Formation. This fact is quite incompatible with the previous interpretation of the westernmost Brandwacht-Waaihoek contact as an unconformity between Malmesbury and Klipheuwel Formations.
4. The large-scale distribution of mesoscopic Early structures suggests that they have been obliquely superimposed upon, and disguise the major tectonic element of the area, a large WNW-ESE trending synform (?) which can probably be linked with the postulated tectonic discontinuity, or slide, at the base of the Brandwacht Formation.
5. The broadly conjugate geometry of the major Late structures and the sense of rotation of the principal Late cleavage with better development are apparently mutually contradictory features of the third phase of deformation. On analogy with similar phenomena in other fold belts, however, this paradox may indicate the close genetic relationships of the second and third phases of deformation, and the thrust movements which brought highly sheared granitic rocks to their present position in the south of the area.
6. The latest weakly-developed structures may have formed in post-Cape folding movements, but all earlier structures form part of an orogenic deformation sequence that has an essential unity. The name "Saldanian" is proposed as a general term for this major episode.

PART II

THE PRE-CAPE FORMATIONS OF FRANSCHHOEK AND KAAIMANSGAT

A. INTRODUCTORY REMARKS

1. Previous Work

The earliest recorded work in these areas is that of officers of the Geological Commission of the Cape of Good Hope in 1898. Schwarz (1898, p. 29-33) described the Malmesbury "clay-slates and porphyries" of the French Hoek valley, noting the presence of a conglomerate in part identical with that from the Cango Beds near Oudtshoorn, the latter being referred to "as a series probably younger than the Malmesbury Beds" (op.cit., p. 32). Rogers and Schwarz (1898a, p. 39-40), after a brief visit to the Elandskloof inlier, recorded that "...the rocks resemble closely some found in the Worcester district. The sheared sandstones, shales and conglomerates are like those of Klein Berg, about ten miles north-west of Worcester..." (op. cit., p. 39); they noted also the presence of granite and quartz-porphyry there.

Rogers and du Toit (1909, p. 47-48), observing that the conglomerate at the high nek south of Franschhoek contained pebbles of quartz-porphyry and granite, maintained that the contact between the granite and conglomerate at that place was a sedimentary unconformity. They therefore proposed that the "French Hoek Beds" should be regarded as younger than the main bulk of the Malmesbury Series and the granites intrusive into the latter.

Haughton (1932, 1933) on the other hand highlighted, in his description of the French Hoek Beds of the Klapmuts-Agter Paarl district, the apparent association of extrusive and intrusive acid igneous rocks with the quartzitic sedimentaries. He tended to believe that the French Hoek Beds were not, in fact, younger than the main intrusions of Cape granite, but that they were deposited almost contemporaneously with acid volcanics which followed immediately upon the main Malmesbury sedimentation, and heralded the main phases of pre-Cape diastrophism and magmatism.

De Villiers, Jansen and Mulder (1964, p. 34) rejected Haughton's identification of acid lavas in the Franschhoek formations; they regarded the so-called felsites, rhyolites and agglomerates as being clearly of mylonitic or cataclastic origin. They supported the earlier observation of a sedimentary contact between sediments and granite at Keerwedernek and, assuming the older, sheared granite to be post-Malmesbury age, were led to correlate the Franschhoek formations with the Klipheuwel. Those smaller intrusions of a distinctive granite porphyry quite obviously of post-Franschhoek age were regarded as belonging to a much later, post-Klipheuwel phase of acid magmatism (op.cit., p. 31). Scholtz's (1946, p. xlviii) concept of a "slightly younger" phase of the Cape granites was therefore significantly modified in this work. The pre-Cape formations of Kaaimansgat were similarly regarded as Klipheuwel

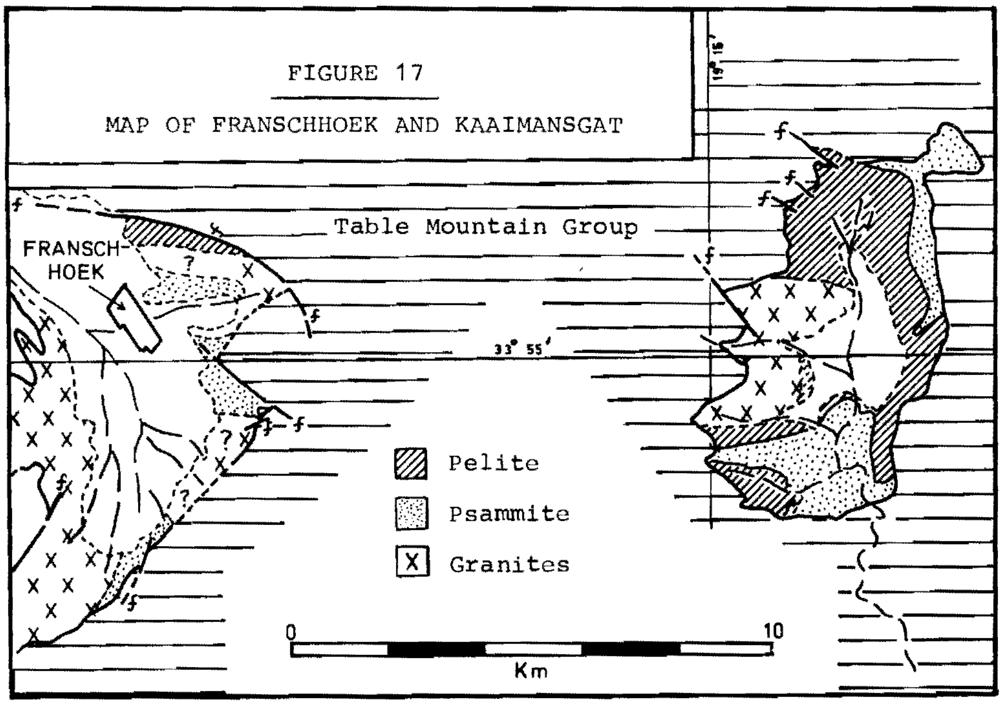


FIGURE 17

MAP OF FRANSCHHOEK AND KAAIMANSGAT

correlates, the formations of the southern part being lithologically not unlike those of Franschhoek. Here, too, a large granitic mass of "post-Klipheuwel" age was mapped.

2. Present investigation

As with the pre-Cape formations of the Worcester area, the present approach to the problems of these southern areas was primarily aimed at the reconstruction of structural geometry, this aspect having been somewhat neglected in previous investigations. Unfortunately conditions of exposure are poorer still in the latter areas than in the former, and it was found that the analysis of structure could not be pursued with the same degree of rigour. The following discussion of the structure of these areas therefore follows a looser pattern. The formations at Franschhoek first, and then Kaaimansgat, are treated in a more qualitative or descriptive manner than is the case for the formations discussed in PART I.

B. STRUCTURAL ANALYSIS AT FRANSCHHOEK

1. Brief description of formation

The pre-Cape rocks of the Franschhoek valley are a fairly distinctive formation having, for the most part, little obvious lithological affinity to the greater mass of so-called Malmesbury beds. The main reason for this is the predominance in the Franschhoek succession of a generally light-weathering, massive, quartzitic rock type, often dark-grey or brownish when fresh. This rock, which is described by de Villiers, Jansen and Mulder (1964, p. 27) as a "subgreywacke", consists of angular and unsorted quartz grains suspended in a matrix of strongly-oriented, fine-grained sericitic material and quartz. It may once have been significantly felspathic. Scattered pebbly inclusions are common, and occasional thin intercalations of more pelitic material are also to be seen.

Higher up in the succession pelitic rocks may become gradually more predominant. A synform above Franschhoek Pass is cored by a dark, slaty rock, and at La Cotte and north of Franschhoek highly-weathered slates and wackes appear to underlie the lower mountain slopes.

Conglomerates, and conglomeratic bands in the immature quartzites, are also a characteristic feature of the Franschhoek beds, being particularly well-developed near what appears to be the base of the succession south of the village. The typical Franschhoek conglomerates consist of a large range of sizes of rather angular pebbles, cobbles and boulders, some having longer dimensions in excess of 30cm. A variety of rock types are included in the coarse sandy matrix, but sheared and altered "granitic" rock types and fine-grained quartzitic material predominate.

The presence of acid volcanic rocks has generally been taken as characteristic of the so-called "French Hoek Beds" (cf. Haughton, 1932; 1933), but in the course of the present investigation no such material was observed to be interbedded with the deformed sedimentary rocks. It instead appears that parts of the highly-altered, older "granite" may previously have been mistaken for volcanic rocks in the Franschhoek sequence. For instance, outcrops between the deformed sedimentary rocks near the Franschhoek Pass and those just east of Keerwedernek are mainly of a rock type which is easily taken for a coarse, gritstone with large, irregular fragments of quartz. Because of poor exposures, Schwarz (1898, p. 32) could not decide whether this was a "sheared quartz porphyry" or a "conglomerate".

A close inspection of this rock shows tattered and broken quartz of varying shape and size embedded in a fine-grained sericite and quartz matrix which generally shows a strong degree of preferred orientation. Occasional more densely sericitic patches appear to be vestiges of original felspar in the rock. Preferred orientation even in these suggests that some alteration of an originally granitic rock had been effected before the tectonic foliation was imposed, although the whole appearance of this strange material could be the result of cataclastic processes which operated during the deformation of the Franschhoek formations. The so-called "quartz-porphyry" pebbles whose presence in the conglomerates led earlier workers (e.g. Rogers and du Toit, 1909; de Villiers et al., 1964) to the conclusion that the Franschhoek beds are younger than the bulk of the granite to the west, have an essentially similar composition.

Only on a weathered surface does this rock bear any reasonable resemblance to the true quartz- or granite-porphyries which, as found in the La Cotte stream bed and in parts of the Stellenbosch-Kuils River pluton (Scholtz, 1946) on the west of Franschhoek, are attractive rocks with white and pink felspar and clear quartz phenocrysts of varying size set in a dark-grey, very fine-grained matrix (de Villiers et al., 1964, p. 31). It is similar in appearance, however, to some of the cataclastic rocks which have been described from the Cape granite plutons.

These observations tend only to confirm the view that at least a fair proportion of the granitic-looking rocks in the Franschhoek vicinity are the basement upon which the pre-Cape sedimentary rocks here were deposited, and together with which they were deformed.

2. Structural Geometry

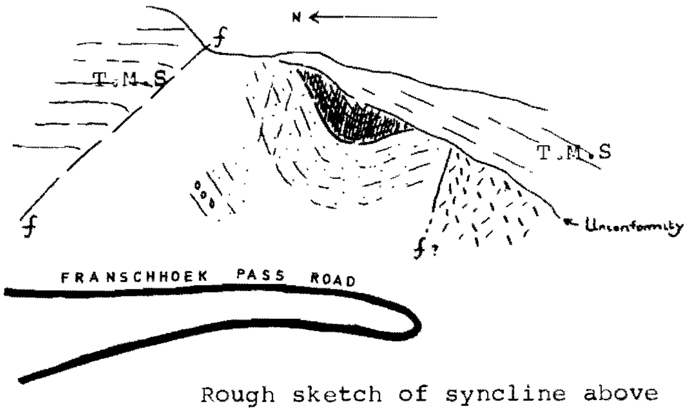
On the Worcester-Caledon Sheet (de Villiers et al., 1964), the broad structural picture at Franschhoek is conceived in the following way: the succession, traced away from the Keerwedernek contact, is regarded as dipping fairly regularly to the north; beginning with the thick conglomerate (Kl_1 R_1), it passes upwards into the quartzose "subgreywacke" (Kl_1 Qw_1) near Franschhoek Pass, and then into more argillaceous material (Kl_2 S_1) north of La Cotte stream. In the present investigation, however, the structural picture was found to be not as simple as this, although the concept that an increasingly higher level in the sequence is exposed as one moves northwards from the Keerwedernek contact seems nevertheless to be a valid one.

The statement in de Villiers, Jansen and Mulder (1964, p. 30) that "... Die Klipheuwel formasie in die vallei van die Bergrivier vanaf die wesgrens van die gebied tot naby Lategan stasie is nie geplooi nie, en selfs in die voorkoms by Franschhoek is geen plooie waargeneem nie. Die lae het wel hoë hellings en is geskuifskeur, maar die verskynsels kan aan die latere opskuiwingsbewegings toegeskryf word...", conveys an incorrect impression of relationships at Franschhoek. A large, synformal fold was found in the best-exposed part of the stretch of pre-Cape outcrop between Middenkransberg and Keerwedernek (See Map II) to which the structural analysis was necessarily confined. The structural data from exposures farther to the south-west leave no doubt that the Franschhoek beds have indeed been folded, and probably in a more complex manner than at the above-mentioned locality.

At Franschhoek, the only outcrops to provide a coherent picture over a reasonable area were those in the vicinity of the Franschhoek Pass hairpin bend. Here a thick sequence, amounting to several hundred feet, of the typical pebbly grit and massive quartzite is followed by some dark, sandy slates in which are to be found occasional thin gritty or pebbly bands. These more argillaceous rocks are preserved in a large and obvious synform. The fold has a fairly straightforward structure; the axial-plane - defined principally by the slaty cleavage in the pelites - strikes and dips at about 250/80N, and the axis trends and plunges at about 070/30. The latter is roughly defined by the poles to bedding and also by a few measurements of a bedding/cleavage intersection lineation. (Refer to the northernmost fabric diagram on Map II).

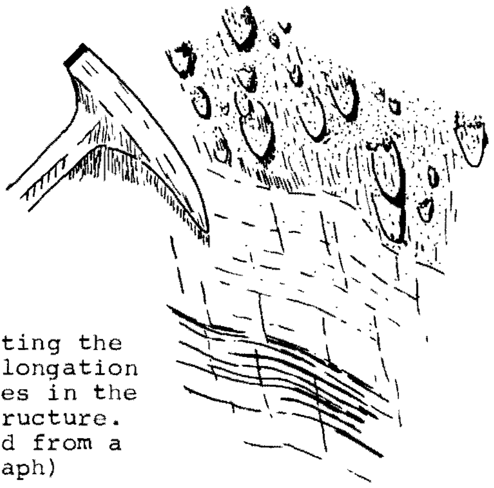
FIGURE 18

A.



Rough sketch of syncline above Franschhoek Pass road. The structure occurs in a grit-slate succession, and terminates abruptly in the south against cataclastic-looking rocks.

B.



Illustrating the strong elongation of pebbles in the above structure. (Sketched from a photograph)

The sketch-plane roughly represents s_1, and the large angle between the s_0/s_1 intersection and the elongation is clear.

There are no fabric elements of a later generation than those recorded. The rocks are, however, complexly-jointed (mainly as a result of post-Cape stresses?), and occasional kink-bands (045/45SE) were observed in the slates.

In the north the Franschhoek Pass synform terminates against the downfaulted Table Mountain Sandstone of Middenkransberg. Shortly before this is reached the lower, coarse gritty lithologies appear, showing no fabric apart from a vague foliation and late joints. The bedding here appears to dip rather steeply to the south, passing into a moderate northward dip of about 290/40N as the hinge surface of the structure is crossed. A very short distance to the south of this, the uniform and poorly-bedded quartzite gives way suddenly to a rock type which looks very much like a sheared, coarse arkose or gritstone; this is the rock which, in the previous section, was described as a probable cataclasite. The contact between it and the quartzite is parallel to the axial-plane of the synform, and can be seen in places to cut across the bedding of the quartzite at a high angle. This is obviously a plane of tectonic dislocation, a fault or steeply-dipping slide, of pre-Cape age.

South of this, the quality and extent of exposure worsens, and between the Franschhoek Pass and the slopes leading up to Keerwedernek, there is in fact very little of the pre-Cape to be seen. The massive, greenish-grey "grit" figures prominently in the scattered outcrops of this area, but some are of quartzitic and conglomeratic rocks of a more obvious sedimentary origin. It is impossible to say what their overall structural relation to the cataclastic-looking rock is. A few scattered measurements of the vague sedimentary bedding of some of these outcrops suggest that folding took place along axes which, in contrast to the E-W structure of the Franschhoek Pass synform, trend more or less N-S. They define a fold-axis, which may not be real, trending and plunging at about 190/20. The main tectonic foliation recorded here strikes and dips at about 020/70E. It therefore seems as if a rather abrupt change in the structure of the Franschhoek formations occurs across the contact of the Franschhoek Pass beds with the enigmatic sheared rock to the south.

Still farther to the south-west, above the farm Hillside, a major development of conglomerate is to be seen. Between this and the Keerwedernek contact the formations consist largely of massive, grey quartzitic rocks, with occasional conglomeratic and slaty intercalations. Over much of the area fabric elements, bedding in particular, are almost impossible to record because of the massive nature of the rocks, and unfortunately the few scattered measurements which were obtained give a rather confused picture.

It appears (refer to the southernmost fabric diagram on Map II) that folding has taken place along axes which are more or less N-S or NNW-trending. The main tectonic foliation strikes between 300° and 030° - coarse, irregular lithology could have something to do with this variation - and stands more or less vertically. Bedding appears to have steep, easterly dips mainly. The very few measurements on cleavage/bedding intersection lineations are of interest in that there is some considerable variation between them. This may indicate that they are superimposed upon earlier fold structures, but under the present poor conditions of exposure it is impossible to express this with any more conviction. Presumably the formations between the Hillside and Keerwedernek conglomerates are preserved in a syncline or downfolded structure, but the available evidence does not permit a detailed reconstruction.

A fabric element which occurs throughout the terrain, but which has not yet been mentioned, is the impressive subvertical linear structure formed by the aligned long axes of conglomerate pebbles. In the Franschhoek Pass synform it can clearly be seen that this does not coincide with the bedding/cleavage intersection lineation or the B-axis of the major fold-structure. In the older terminology of Sander (1930), this element would be termed an "a"-lineation, with reference to the so-called direction of "transport" in the rocks. Lying in the axial-plane cleavage (the XY principal plane of strain), the pebble elongation corresponds to the direction of maximum extensive strain (X).

3. Summary

1. The general character of the conglomerates and associated gritty, quartzitic rocks of the Franschhoek Formation, suggest that they were assembled fairly rapidly after having been transported only a short distance from a nearby mass of pre-Franschhoek basement.

2. The Franschhoek Formation has been severely deformed, but unfortunately, exposures are too poor to allow a detailed reconstruction of major tectonic structures, or a tectonic history. The main structural problem concerns the difference between the Franschhoek Pass synform and the exposures further south.

3. Detailed investigation of the granites was beyond the scope of this work, which merely serves to reinforce the view that there are granites of greatly differing age at Franschhoek. The older, sheared granitoids pre-date the deposition and deformation of the Franschhoek Formation; the younger granite porphyry is quite obviously of later age than the main Franschhoek deformation.

4. On account of their structural state, the Franschhoek rocks do not resemble the formations at and about Klipheuwel, and certainly cannot be correlated with the latter.

C. STRUCTURAL ANALYSIS IN KAAIMANSGAT

1. Brief description of formations

On the Worcester-Caledon sheet (de Villiers, Jansen and Mulder, 1964), the pre-Cape formations displayed in the great inlier north-west of Villiersdorp, known as Elandskloof or Kaaimansgat, are shown as belonging to the middle and upper stages of the "Klipheuwel Formation". They are said to be intruded on the west by a fairly large mass of the "younger", (post-Klipheuwel) granite and granite-porphyry.

On the sheet, the pelitic rocks in the south-west (Kl_2S_1) are separated, by a supposed connection between the southern and northern quartzites (Kl_2), from the pelites and wackes (Kl_3Qw_1) on the south-east side. On the basis of the structural picture which has been obtained in the present mapping, it now seems quite certain that this connection does not exist, and that the pelitic rocks north of the southern quartzite, in the south-west and south-east of the valley, occupy the same stratigraphic position.

In the extreme south of the same map, a fairly sizeable mass of younger granite porphyry is shown to intrude, and to be virtually enclosed by the Kl_2 quartzite. The area which this occupies, the Longkloof, separated from the main part of the valley by a prominent E-W striking ridge, is very poorly exposed, and its lower slopes are covered by dense, impenetrable Hakea. Along the stretch of generally poor outcrop below the Table Mountain sandstone, however, no sign of granite porphyry is to be seen; the rocks here being slaty pelites and wackes similar in all respects to those occurring north of the quartzite ridge.

The larger mass of granitic rocks on the western side of the valley appears to have been in existence prior to the deformation of the surrounding metasedimentary rocks. Good exposures are very rare, but wherever it is seen, it is highly sheared and cataclastically altered. In Perdekloof, in the south of the mass, a highly siliceous cataclastic rock, showing relicts of crushed and altered felspar, is intruded by a small boss, and thin dykes of younger undeformed granite-porphyry practically identical in appearance to that found at Franschhoek. The igneous origin of the dyke-like "gp_2" masses shown within the Kl_2 quartzite is not at all obvious. These, too, have a markedly cataclastic appearance, and may have been generated out of the surrounding sedimentary material during, or at a late stage in, the main deformation.

2. Structural Geometry

With respect to the structural geology of the Kaaimansgat, de Villiers, Jansen and Mulder (1964, p. 30) note briefly that: "Die voorkoms in die Kaaimansgat is 'n antiklinorium wat noordooswarts duik; ondergeskikte plooing is opmerklik in die suidvleuel van die antiklinorium". The results of the present investigation indicate that this broad description must be further qualified.

It is quite true that, on a large scale, the pre-Cape structure of the Kaaimansgat is that of a large, north-easterly- plunging antiform. It is important to note, however, that this structure appears to have been formed relatively late in the sequence of pre-Cape deformation, and that the s-surface which has been folded into this structure is itself probably of tectonic origin. Secondly, the "subordinate folding" in the southern part of the Kaaimansgat displays quite different style and geometry, and the structures here are plainly of an early generation or phase. The broad structural picture in Kaaimansgat is of a large, open NE- trending Late fold, mainly evident in the north, with Early, S- or SSE- plunging folds on the southern limb; in detail, it may be more complicated than this.

Structural analysis here is greatly hampered by the limited extent of good exposure, and in places by the nature of the lithology also. In the massive quartzites, for example, it is difficult to obtain any mesoscopic structural information other than rough measurements of the principal tectonic foliation. In the extreme south-east particularly, it is mainly from good exposures of the pelitic rocks surrounding the quartzite that structural data has been gathered.

In the south-east, the nose of an Early fold is outlined by the main quartzite and cored by phyllites and slaty wackes. The cleavage (s_1) in these rocks, striking roughly NE and dipping steeply to the SE, is axial-planar to this structure. The axis of the fold trends and plunges at about 180/60, and it is therefore very nearly a reclined or neutral structure. It is, of course, a steeply-plunging antiform, and if the previous interpretation of the stratigraphy is accepted, it must be a downward-facing fold; the pelitic "Kl_3" rocks here plunge southward beneath the "Kl_2" quartzite. However, as no reliable way-up indicators have been found here, there is no way of telling whether or not this is the case.

The fabric diagram for the southern part of the area shows poles to the main foliation, s_1, and the Early lineation, including axes of Early minor folds,from this antiform and also from other areas of the quartzite-phyllite succession here. There are no penetrative planar structures later than s_1 in any part of this area, and the wide scatter of poles to this structure is due mainly to a very gentle and large-scale swing in strike, from more or less E-W in the south-west to more NE or NNE farther east; a few very open and rather irregular minor folds of s_1, roughly coaxial with the Early lineation and fold axes, are the small-scale expression of this apparently unimportant Late deformation.

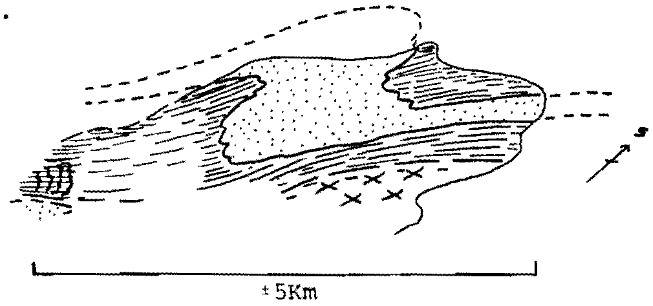
In the quartzites, bedding (s_0) is generally sheared out of recognition, while in the pelitic rocks the compositional banding is for the most part parallel to s_1, into which it has obviously been tectonically transposed. Small isolated tectonic inclusions and intrafolial folds (Turner and Weiss, 1963, p. 117) have their axes oriented roughly parallel to the well-developed, steeply-pitching mineral lineation in the phyllites.

Farther north along the outcrops fringing the eastern side of the valley, there is a lithological change to more gritty, massive types of "greywacke". The finely-foliated character of the more pelitic rocks disappears, to be replaced by a massive compositional banding (?s_0) to which a rough foliation or cleavage is parallel. The fine lineation characteristic of the phyllites farther south also disappears though a very much more vague, steeply-plunging linear element is still seen in places.

The above-mentioned planar structure, the poles to which are the main element of the diagram for the east central part of the valley, generally tends to strike E-W or even ESE and stands almost vertically; very steep dips to the south predominate. In places, this surface is folded into relatively large structures at least some metres in

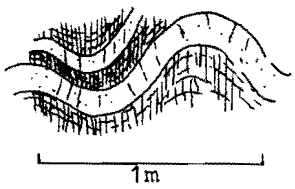
FIGURE 19

A.



Schematic "down-the-plunge" or profile view of the Early major structures in southern Kaaimansgat, based on the assumption that the minor folds in the area are strictly homoaxial and that, with the prominent lineation in the phyllites, they represent an axis of large-scale cylindroidal folding. This assumption is probably not correct, but it is interesting to note that most minor folds, down to a scale of a few centimetres, are practically identical in style to the structure illustrated above. The coincidence of the axes of these generally small structures with a lineation which probably marks a direction of stretching or elongation in the rocks, may imply either fold superposition or deformation under conditions of constrictive strain. In either case the large-scale structure will be non-cylindroidal, and the profile outlined above cannot be expected to persist in the axial direction.

B.



Late minor fold from Louwshoek area (northern Kaaimansgat) with roughly axial-planar, "strain-slip" or crenulation foliation, s_2.

wavelength, and this is responsible for the scatter of poles in the diagram. The large size, and the "concentric" style, of these minor folds seems to be directly attributable to the massive nature of the lithology in these parts.

These folds, which occur mainly in an area about Perdestal, just south of the north-eastern mass of pre-Cape quartzite, have axial trends of about 130°, and plunge between 60° and 80° in this direction. They are characterised also by the local development of a rough fracture cleavage (?s_1) parallel to their axial-planes, in places giving rise to coarse cleavage mullions. The fold axial-planes strike between NE and E-W. Despite the general difference in size, style and appearance, these folds have roughly the same axial-plane orientation as those farther to the south, and are probably of the same generation; their axial orientation is somewhat different, however, trending more towards the south-east than S.

This last point raises the question of whether the Early folding in the southern part of the Kaaimansgat is not more complex than might at first appear from the fair homogeneity of the area with respect to the Early lineation and fold axes. Apart from a slight and possibly significant variability in the orientation of the Early intersection lineation, the steeply-pitching, almost reclined orientation of the minor and major folds over most of the area, is itself a feature which requires some explanation.

In the diagram representing the principal fabric elements of the northern part of Kaaimansgat, the data come mainly from pelitic outcrops fringing the north-west side of the valley; for the quartzite in the north-east, like that in the south, is massive, sheared and not well-exposed. The general structure of the area is that of the crestal region of a very large antiform, some 3-4 Km in wavelength; the major portion of the northern limb of this fold is obscured by Cape System cover in the north-west. The general inclination of the principal foliation (?s_1) in the above-mentioned outcrops is therefore moderate, with dips to the north or north-east ranging between 20° and 50°.

Minor folds in s_1 here are open, more or less symmetrical buckles of a "concentric" or flexural-slip type (Whitten, 1966a, p. 147) with no obvious axial-plane cleavage or foliation in many or most cases. This seems to be in accordance with a general conformity of structural style between the large-scale antiform and the small-scale minor folds. In the more southerly exposures below Louwshoek Peak, just north of the granitic mass in the west of the valley, these minor structures plunge to the NE at about 30°. Farther north than this, in the north-west "hoek" of the valley, these Late folds have a rather sharper style in places, and a locally penetrative crenulation or strain-slip foliation (s_2) is developed. This later cleavage, where best developed, strikes roughly NNE (010-020°) and dips very steeply to the east. The same Late folds in this part plunge more towards the north.

There is a general lack of strict homogeneity in the diagram for the Late folding in the northern Kaaimansgat, but this is probably to be expected with deformation of this generation and type.

3. Summary

1. The Kaaimansgat Formation, of quartzitic and pelitic rocks, is also associated with sheared granitoids, though not as intimately as the Franschhoek Formation. Younger granite prophyry, identical to that at Franschhoek, has also been found here, though in very restricted occurrence.

2. The formations are very severely deformed. The southern Kaaimansgat is characterised by large, tight, Early structures, with steep S or SSE plunges; the axial-planes of these strike roughly ENE. The northern Kaaimansgat is characterised by a larger, open, Late antiform which plunges gently NE.

3. The geometrical relationship between Early and Late structures is not completely clear, and the Early structures seem to vary in style and orientation for some reason. It is unlikely that the reclined orientation of the latter is due to the bending of the axes of N-S-trending recumbent folds into steeply-plunging attitudes by the Late NE- or ENE-trending major fold. It seems more likely that the southern reclined folds were produced by an Early deformation which involved two superposed phases, or a complex pattern of three-dimensional strain.

CONCLUSION

In the Introduction to this work, a brief review of the history of research into, and nomenclature of, the pre-Cape formations of the Western Province was given. The object of the following section is to tie together, as far as possible, the results obtained in the different areas of this work, and to show their relevance to earlier controversies. It must, however, be stressed that the ideas expressed here, expecially in connection with wider stratigraphical aspects, are tentative, and will no doubt require revision when more information on this very difficult and imperfectly known terrain becomes available.

1. Structural and stratigraphic comparisons

Detailed comparison between the different pre-Cape inliers is rendered extremely difficult by the great complexity of the older formations. Even in the case of the Franschhoek and Kaaimansgat exposures, which are separated by only a few kilometres of Cape System cover, comparisons and correlations can be made only in the most general terms.

From the stratigraphic point of view, the formations in these southern areas show some mutual affinity, if only in the following two respects. Firstly, the massive quartzites of the Kaaimansgat Formation are rather similar to those in some parts of Fransch Hoek valley, and the general facies character of the formations is much the same. Secondly, the close association of both the Kaaimansgat and Franschhoek Formations with older granitoid rocks suggests that both represent roughly the same level in the pre-Cape sequence, the more pelitic Kaaimansgat rocks perhaps coming from a slightly higher or more interior part of the pre-Cape basin or geosyncline.

Structurally, no detailed relationships can be elaborated. The general tectonic trend of these formations is roughly E-W, and there seems to be no reason for doubting that the main deformation of the Franschhoek Formation, however complex this may be in detail, is not the same as the main or Early deformation of the Kaaimansgat Formation.

Similarly, the main deformation at Kaaimansgat can probably be correlated with Phase M at Worcester. These are, of course, differences between the broad tectonic styles in each of these areas. In the future, when the different expressions of the Saldanian Episode in different parts of the Western Province are better known (and some mention of these differences was made in the latter sections of Part I), it may become possible to relate these to a large-scale pattern of infrastructure and suprastructure (cf. Zwart 1963) in the orogenic belt. The presence of such a pattern will probably mean that it is impossible to correlate individual tectonic phases over wide areas, for each zone or regime of the belt will have reacted differently to the applied stresses.

Stratigraphic comparison between Worcester and the southern areas revolves about one main point; namely, the general similarity of the lower formations (i.e. Waaihoek and Glen Heatlie) at Worcester to the Franschhoek and Kaaimansgat rocks. The broad correlation of the Franschhoek, Kaaimansgat and Waaihoek Formations seems, in spite of their spatial separation and local structural differences, to be quite reasonable; the rocks have definite lithological and facial resemblances. This is particularly true of the quartzite-phyllite sequences at Waaihoek and southern Kaaimansgat (cf. Rogers and Schwarz, 1898a, p. 39).

De Villiers' grouping of these formations (de Villiers, 1956; et al., 1964) is therefore affected only as far as correlation with formations of the Klipheuwel Group proper (i.e. the Klipheuwel-Kalabaskraal, Heuningsberg and Slanghoek beds, among others). In the Worcester area, the demonstration that the greywackes of the Brandwacht Formation rest above the Waaihoek Formation, and that both have been affected by the same main deformation indicates that the correlation of extensive areas of deformed pre-Cape rocks with the Klipheuwel Group is untenable. The occurrence, in the nearby Slanghoek valley, of true Klipheuwel beds, quite dissimilar in appearance and metamorphic condition to the Waaihoek Formation, supports this conclusion.

At Franschhoek and Kaaimansgat, however, the present works confirm the close association of the formations there with older, much-deformed and altered, granitic rocks. In other words, the main feature of pre-Cape stratigraphy which gave rise to the concept of a very much extended "Klipheuwel Formation" is certainly real, and not the consequence of very poor exposure of a geologically complex terrain. This is borne out by relationships, or at least the present interpretation thereof, at Worcester, where similar sheared granitoid rocks are in tectonic contact with the Brandwacht Formation - which, moreover, has a typically "Malmesbury" character.

2. The Boland Group

In these observations lie the bases of a concept of pre-Cape stratigraphy which, though not new, is quite different from that to be found on Geological Survey Sheets 3319C and 3419A (de Villiers et al., 1964). The forerunner of the stratigraphic model outlined below is to be found on maps of the pre-Cape terrain compiled by L.P. Rabie (Rabie, 1948; Univ. Stell., 1948).

The Worcester area and the regions to the east, towards Robertson, can be regarded as the type area of a geosynclinal sequence called the "Boland Formation" by Rabie, and here renamed the Boland Group. The internal stratigraphy of the Boland Group has been excessively complicated by polyphasal folding of Alpine character, but its broad outlines nevertheless appear to be preserved (cf. Univ. Stell., 1948). The lower parts include dark, occasionally graphitic and calcareous pelites, fairly clear orthoquartzites, and limestones in places. The Waaihoek Formation though non-calcareous, may belong to this lowermost division. With its similarities to part of the Kaaimansgat Formation, it may link the lower Boland Group of the Worcester area to the yet more basal, sparagmitic formations at Franschhoek. Higher up in the succession, though still within the lower Boland, immature wackes and pelites, of which the Glen Heatlie Formation is perhaps representative, make their appearance. Finally, the main flysch-like greywackes, represented by the Brandwacht Formation, form the upper division of the Boland Group.

Any more comprehensive account of the Boland Group is at present impossible, and must be attendant on further detailed structural work in the area between Worcester and Robertson. It is also likely that the question of facies will have to be taken into consideration, for instance, in the apparently increasing importance towards the east of a limestone-black shale association in the lower Boland formations (cf. Univ. Stell., 1948). In the Cango Group near Oudtshoorn, which in broad outline shows a strikingly similar sequence to that of the Boland Group (cf. Stocken, 1954; Mulder, 1954; Roussouw et al., 1964), the limestone facies is an even more important element of the lower parts. In this connection it is interesting to note that the resemblances between the Boland Group and the Cango Group are, in general, greater than between the former and the much closer "Malmesbury" formations to the west and south-west. Here too, Rabie's (1948) Swartland-Boland dichotomy, or even de Villiers' (1956) Malmesbury-Klipheuwel distinction, may point to a problem of facies, rather than indicate distinctly different chronostratigraphic elements.

This problem of the relation of the Boland Group to the "Malmesbury" formations farther west must await the results of work presently being carried out in the Malmesbury district. Preliminary observations (Newton, 1966) suggest that the internal stratigraphy of the so-called "Malmesbury" may not be simple, and that two different groups of formations may have been lumped together under one name. This, incidentally, is one of the reasons for which it appears preferable to abandon, or at least suspend the use of, the traditional term "Malmesbury", and for which Rabie's (1948) nomenclature, which lay conveniently to hand, has been followed. Whether or not the older formations of Newton (1966) can definitely be separated from the apparently younger group, it seems reasonable to expect that a fair proportion, if not the majority of the pre-Cape formations previously called "Malmesbury" can be correlated with the Boland Group.

3. The Cape Granite problem

The main difference between the Boland Group as described here, and Rabie's "Boland Formation" as presented on his maps (1948; Univ. Stell., 1948) concerns the view of their relation to the Cape Granite (if it is still possible to conceive of the latter as a unitary entity). On the Worcester-Swellendam map the granites are regarded as intrusive into the "Boland Formation", and this is true also of previous and subsequent maps.

Though the granitic rocks were specifically excluded from the scope of this study, the contact relationships of the Brandwacht Formation with the granitoid rocks, and the development of s_1 in both, are clear and strongly suggest that the older view of it as intrusive is seriously in need of revision. The same is probably true of the Bruintjies Hoogte mass near Swellendam, which Scholtz (1946, p. lxiv) mentions as being foliated. Only the large Robertson, or Wolwe Kloof pluton may be excepted, mainly by virtue of its size and form. Scholtz (op. cit.) records that P. L. du Bruyn mapped foliation and lineation arches in this mass, and he interprets these as primary flow structures. However, from the only published detailed description of the rocks, that of Rastall (1911, p. 716-718), the following observation emerges: "Since the inner parts of the granite mass ... show no foliation, while the outer parts are much crushed and sheared, it is clear that the intrusion took place before the final foliation, and that the great size of the main mass protected the interior from crushing, while the margin and the peripheral dykes were strongly foliated". From this description it is obvious that the peripheral deformation was of a brittle nature. In addition, such observations on the immediately surrounding "Malmesbury" rocks as " ... there is little or no evidence of thermal metamorphism... rapid alternation of granite and apparently unaltered sediment ... but no development of contact minerals" (op.cit., p. 715), and the recording of the presence of "phyllite-gneiss" (mylonitic material?), put even the "transgressive" Robertson pluton in a highly ambiguous position.

Thus, in the pre-Cape of the Worcester-Swellendam mountain foreland, a good prima facie case can be made out on the available evidence, for regarding the granitic rocks as the basement to the Boland Group. Yet, in the past, there has never been any serious doubt concerning the "post-Malmesbury" age, of the Cape granites, "since intrusive relations with sediments of the Malmesbury Series have been repeatedly demonstrated" (Scholtz, 1946, p. li); in the case of the Cape Peninsula granite, the intrusive contact at Sea Point is a classic. Moreover, recent studies (Kolbe, 1965) have shown that all South-western and Eastern (George) plutons are closely related in most aspects of their geochemistry.

There are two main lines along which a solution to this increasingly paradoxical situation may be sought. One is to look for the answer in the "Malmesbury", and, for the time being, to assume that the formations which are intruded by the Cape granites are significantly older than the Boland Group. Until it can be shown that some intruded formations are the definite correlates of the Boland, this explanation may be supposed to hold water. In fact, there are obvious and serious difficulties with this view, which revives the Malmesbury-Klipheuwel concept of de Villiers (1956) but on a much larger scale, and with the true Klipheuwel Group left out.

On the other hand, the answer may lie along the second line, namely in a new approach to the Cape granites themselves. The problem of the sheared and cataclastically deformed granites is a much wider one than is generally supposed, for these rocks have a quite extensive distribution between Saldanha and Stellenbosch (Schoch, 1962). The writer is inclined to suggest that Scholtz's (1946, p. lxxx) postulated subjacent intrusion or batholith, in which the Cape plutons are said to be rooted, is in fact the crystalline basement upon which the Boland Group (and the "Malmesbury"?) was deposited, and that during the Saldanian episode, this basement suffered local remobilisation - not necessarily leading to complete magmatic palingenesis - to different degrees in different places. This hypothesis sheds a new light on Read's (1951, p. 9) opinion that the Cape plutons "made their way in as nearly solid masses * by softening up the country rocks around them". In this view, the transgressive plutons, with their contact metamorphic aureoles and their non-foliated character, are diapiris structures, having risen from the basement like salt domes, on account of their increased bouyancy on partial remobilisation. Smaller dykes of aplite and granite porphyry may be products of local complete melting.

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* The writer's italics.

4. Some geochronological aspects

From the foregoing, it is obviously premature to attempt the construction of a general stratigraphic history of the pre-Cape, or to elaborate at length on wider relationships at this stage. Firstly, the stratigraphic and facies relationships, and the structures of the regionally metamorphosed and deformed rocks are extremely complex, and much more detailed work is required before any clear picture will emerge. Secondly, the Cape granites pose a problem that will have to be resolved.

There can, however, be no doubt at all that all the older formations of the Western Province fall within a belt that has been affected by the very extensive, upper Proterozoic - lower Paleozoic tectonism in Southern Africa (Clifford, 1967). The Cape Peninsula granite has yielded U-Pb-Th, Rb-Sr and K-Ar ages concentrated mainly between 520-470 My,* that is, in Cambro-Ordovician times. (Nicolaysen, 1954; Aldrich et al., 1958; Allsopp and Kolbe, 1965; Schreiner, Basson and Verbeek, 1968).

Bearing in mind the numerous uncertainties, the Rb-Sr isochron of 560± 45 My calculated for the "Malmesbury" sediments of the Cape Peninsula area, and said to represent the date of "isotopic homogenisation" (Allsopp and Kolbe, 1945, p. 1126) by diagenesis or metamorphism of these rocks, can be taken as the approximate minimum age of deposition of the synorogenic facies. The sedimentation of some of the flysch-like, greywacke formations could therefore have extended into Cambrian times. The lower formations of the Boland Group, which were probably deposited under more stable conditions, belong in the Upper Proterozoic, perhaps not very far below the Precambrian-Cambrian boundary.

The lower limit of the Peninsula granite age-spread may closely approximate to the time of uplift and cooling of the (diapiric?) plutons, and the synchronous deposition of the Klipheuwel Group in areas away from the rising granites. Holmes (1953, p. 46) drew attention to the resemblances of the Klipheuwel formations to a red, oxidised, post- or late-orogenic molasse. And Sutton (1965, p. 34-35) has noted that, at the end of mountain-building, "...the cooling of (high-grade) rocks to temperatures at which the liberation of radiogenic elements from mineral lattices ceased and the start of post-orogenic molasse accumulation are scarcely distinguishable events even in a chain as young as the Alps...". There is therefore no problem of fitting Klipheuwel sedimentation in the very small age-gap between granite formation and the onset of Table Mountain Group sedimentation, though Rust's (1967, p. 95) calculation of 505 My for the latter may be slightly too high.

As far as the overall stratigraphic history of the south-western Cape Province is concerned, one of the most interesting features revealed by the radiometric data, is this close relationship in time between the pre-Cape and Cape-Karroo geosynclines. The close spatial and structural relation has drawn some comment in the past (de Villiers, 1944; Scholtz, 1946). There is the general parallelism of major tectonic

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* The assumption of a decay constant of Rb^{87} of $1.474 \times 10^{-11} yr^{-1}$, giving Rb-Sr ages 6% lower than those quoted by Allsopp and Kolbe (1965) yields a better correspondence between Rb-Sr and K-Ar ages for the Cape Peninsula granite.

features, and there is the obvious control over post-Cape structure exerted by the varying competence of the pre-Cape foundation. Broadly conceived, then, the stratigraphic history of these areas is one of practically continuous instability, with closely related subsidence, sedimentation, tectonism and uplift, extending from Upper Proterozoic to Triassic times in a super-cycle lasting some 600 m.y. or more. But to pursue this topic further here is well beyond the scope of this work.

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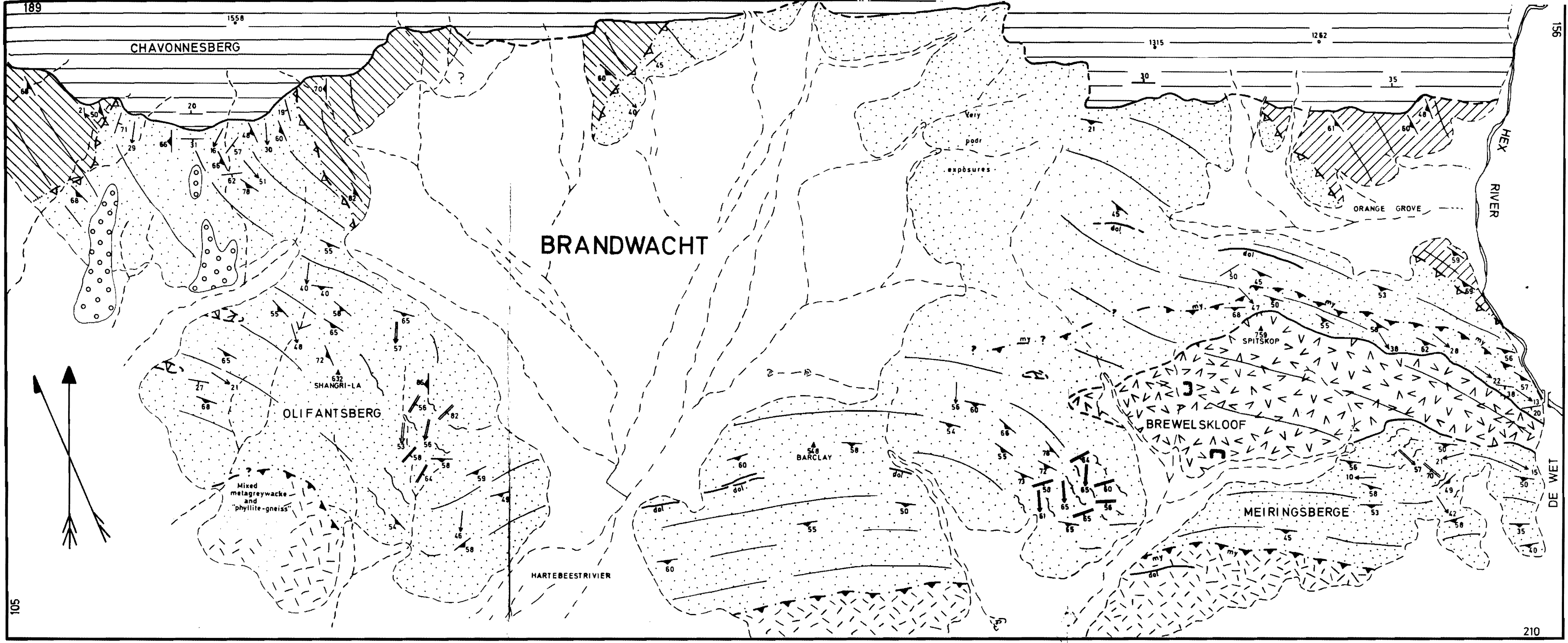


MAP I

GEOLOGICAL MAP

OF THE

BRANDWACHT AREA, WORCESTER

C. J. H. HARTNADY
1969

☐	SAND and ALLUVIUM		
○	PIEDMONT GRAVELS		
☰	QUARTZITIC SANDSTONES	TABLE MOUNTAIN GROUP	
V	ALTERED BASIC ROCKS		
⁘	GREYWACKES and CONGLOMERATE	Brandwacht Formation	BOLAND GROUP
▨	DRAB PELITIC WACKES	Glen Heatlie Formation	
▧	DARK SLATY PELITES with QUARTZITES elsewhere	Waaihoek Formation	
⁄	SHEARED GRANITIC ROCKS		

dol - DOLERITE

my - MYLONITES

BEDDING s_0

REGIONAL FOLIATION s_1

SECONDARY CLEAVAGES s_2. s_3

EARLY LINEATION l_1

LATE LINEATIONS l_2. l_3

STRUCTURAL FORM LINES ON s_1

PHASE O SLIDE

PHASE M THRUSTS

759 SPITSKOP TRIGONOMETRICAL BEACONS – height in metres

1558 FRONTAL PEAKS OF HEX RIVER RANGE – height in metres

QUARRY

THE AREA COVERED BY THIS MAP COMPRISES PARTS OF TOPO. SURVEY SHEETS

Nos. 694	3319 J3	WORCESTER		(1:18,000)
698	3319 J4			
702	3319 J5	NUY		

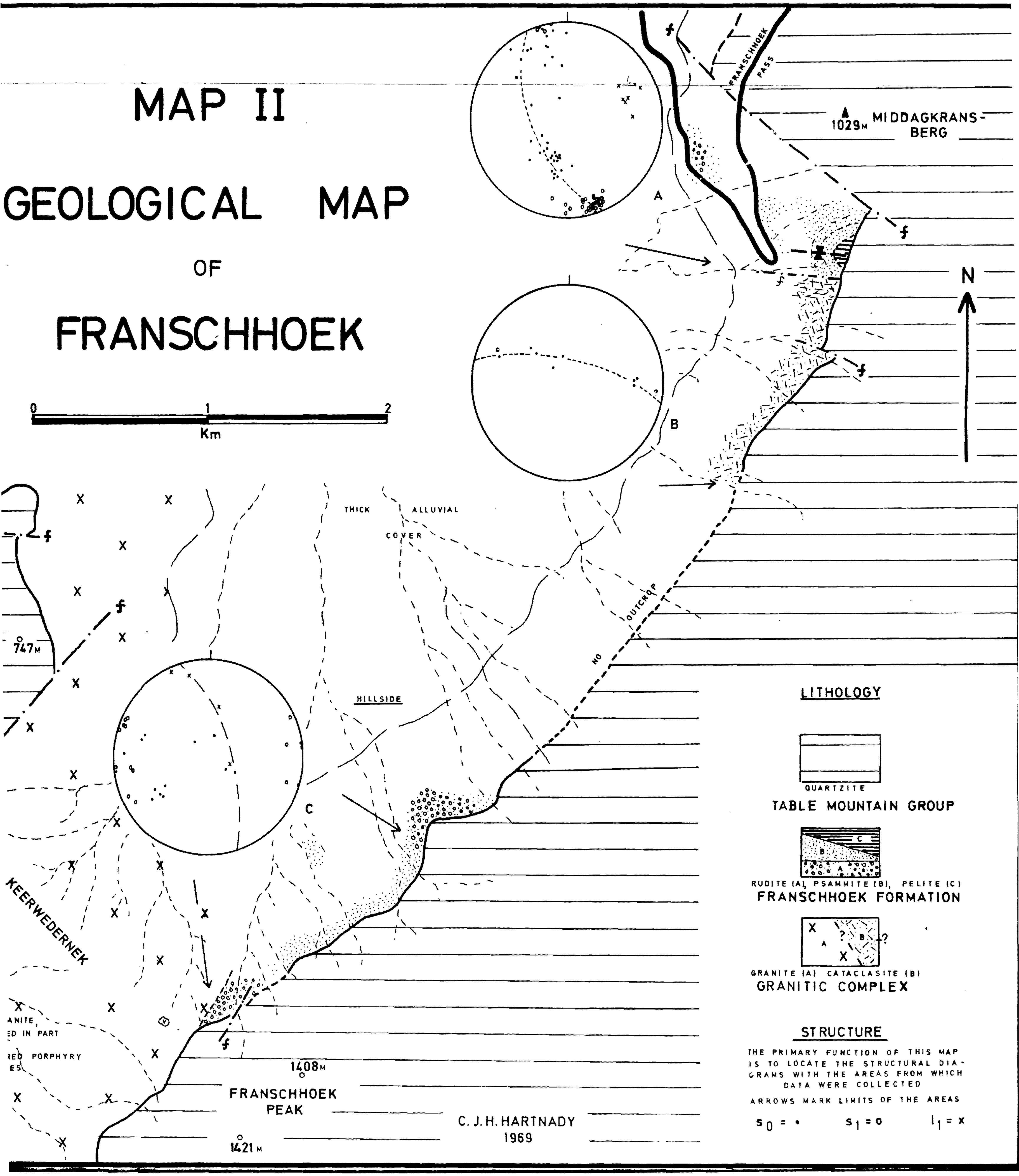
NUMBERS IN MAP CORNERS REFER TO GRID ON THESE SHEETS

MAP II

GEOLOGICAL MAP

OF

FRANSCHHOEK



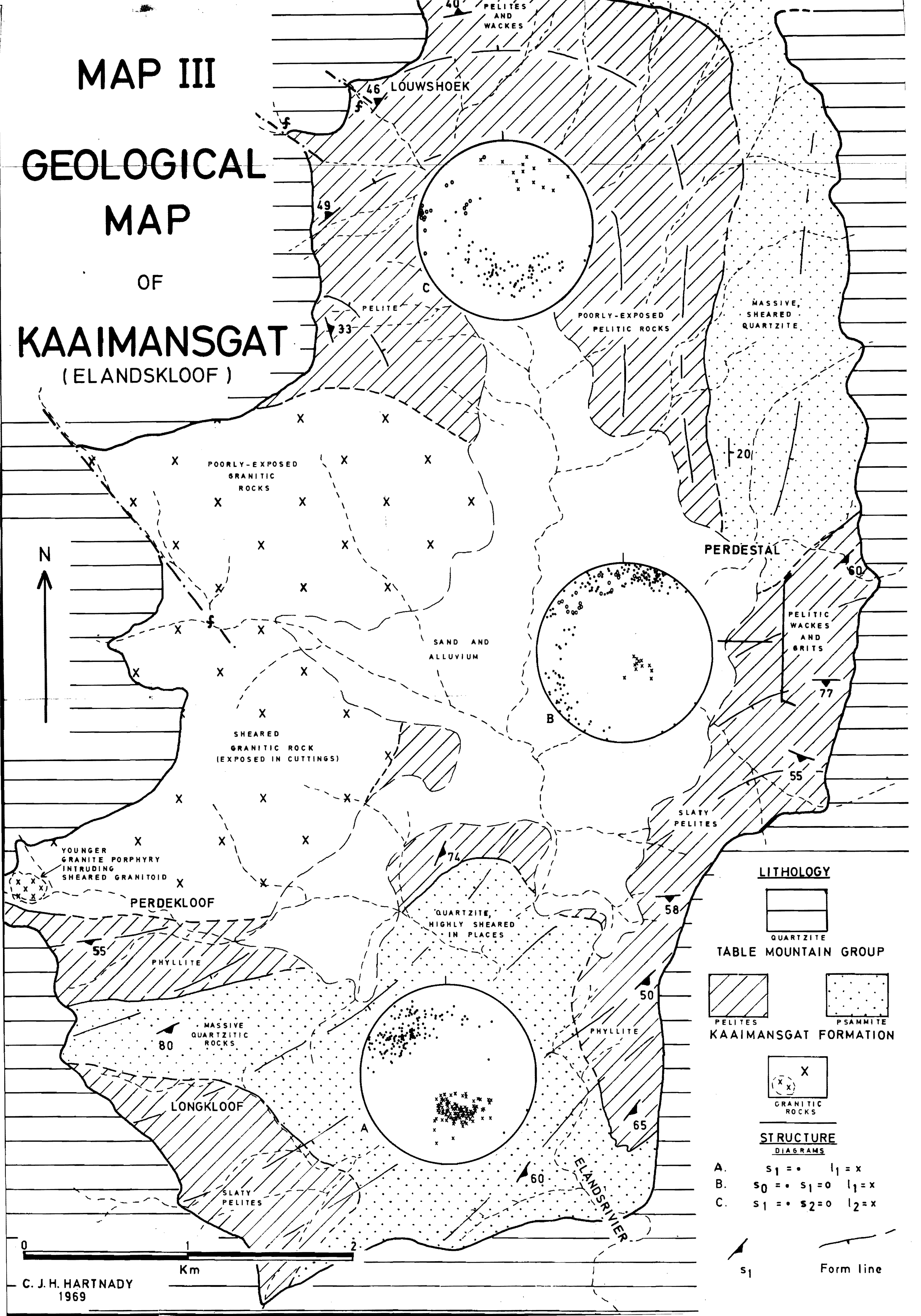
MAP III

GEOLOGICAL MAP

OF

KAAIMANSGAT

(ELANDSKLOOF)



C. J. H. HARTNADY
1969