TECTONIC EVOLUTION OF THE WALDAU RIDGE STRUCTURE AND THE OKAHANDJA LINEAMENT IN PART OF THE CENTRAL DAMARA OROGEN, WEST OF OKAHANDJA, SOUTH WEST AFRICA

by

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tonic igneous activity appears to have been in the form of aplite or quartz-felspar porphyry dykes (G1). The Salem Granite Suite is the most widely represented granitic type and is to a large extent the ultra-metamorphic equivalent of part of the Kuiseb Formation. G2 granite is late syntectonic and shows the effects of the later phases of deformation. The remainder of granitic types are early post-tectonic members (G3, G4, G5) and were emplaced at the peak of M_1 metamorphism. The G5 granite may in part be derived from anatexis of quartzo-felspathic rocks of the Etusis Formation. The Donkerhoek Granite (G6) is post-tectonic and related in time of intrusion to a regional thermal metamorphic event (M_2). In this area, it was emplaced in rocks which had cooled to below peak metamorphic temperature and thus has a definite contact thermal-metamorphic aureole. A relatively small body of orthopyroxene-bearing gabbroic rock (B), was intruded in late syntectonic times. The origin of this rock is uncertain, but the intrusion may be related to a suite of similar rocks further west.

Tectonic evolution of the Waldau Ridge structure and the Okahandja Lineament is interpreted in terms of gravity-initiated deformation due to vertical uplift of the Abbabis Swell relative to the Khomas Trough along the Okahandja Lineament. Compressive forces from the south brought about deformation of the rocks south of the northern margin of the Okahandja Lineament and the development of a zone of "flattening strain" and possible further vertical movement along this zone which developed the features as seen today. These compressive forces were translated to large scale strike-slip movements along the north margin of the Okahandja Lineament at a late stage in the tectonic history of this zone.

It appears likely that the basic pattern of the Waldau Ridge structure, in part owes its origin to compressive forces originating in, and possibly related to, orogenic events in the main trunk of the Pan-African orogenic belt further west.

It is proposed that the major tectonic relationships in the area can be related to subduction and continental collision in the southern part of the Khomas Trough in late Precambrian times.

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I

INTRODUCTION

A. General

An area of approximately 140 km^2 situated some 25 km due west of Okahandja in South West Africa is described in this report. It covers the hilly area of the Waldau Ridge and environs, south of the main Okahandja-Karibib road and is practically bisected by latitude 22° south and largely west of longitude 16° 45 east.

The morphology of this area has been described by Gevers (1963). The general altitude of the area is approximately 1400m and it lies on the south side of the watershed between two major, westward flowing rivers, the Kahn River to the north and the Swakop River to the south. The area is bounded on the west and east by the Osombanda and Waldau Rivers respectively which flow southwards to the Swakop River. The area around the base of the Waldau Ridge, is characterised by gravel terraces into which the younger southward flowing drainage system is incised. Thick alluvium in the course of the sand-choked Osombanda River valley obscures much of the outcrop in the western part of the area.

The land is used largely for livestock farming and access is good, especially when the larger sand-filled river-beds, are used.

B. Previous Work

The general geology of a larger area, (of which this study covers a small part), was described by Gevers (*op.cit.*) as the logical extension to the area described by Smith (1961, 1965) farther west. Gevers (*op.cit.*) described in detail the form of minor structural features in the vicinity Gross Barmen Hot Springs. Hälbich (1970) carried out a structural reconnaissance of the Khomas "synclinorium", re-evaluated Gevers' findings at Gross Barmen and discussed the possible relationship between deformation in the Abbabis Swell and the Khomas "synclinorium".

C. Present Investigation

Initial geological mapping in this area was undertaken by the writer as part of a regional base-metal exploration program for Falconbridge Explorations Limited. Portions mapped in the western part of the area by other staff members (unpublished reports) were re-investigated to gather additional structural information, leading to a complete re-interpretation of the relationship between the lithologies described previously.

Six months were spent on detailed fieldwork during early 1976, subsequent to initial regional mapping. The laboratory investigations, the study of the literature, the compilation of the geological map from 1:36 000 and 1:50 000 aerial photographs onto 1:50 000 topographic maps and preparation of this report were carried out at the University of Cape Town until the end of January, 1977.

D. Acknowledgements

I am indebted to the management of Falconbridge Explorations Limited for permission to use material collected while in their employ and for reference to unpublished information on their prospecting grant areas near Okahandja. Their considerable financial and logistical assistance provided during the course of fieldwork and the granting of extended unpaid leave during the period of research are gratefully acknowledged.

Thanks are also due to the management of Somerset Mining Limited for permission to carry out investigations on a small portion of the area held under prospecting grant by them. The various farmers in the area are to be thanked for their assistance in granting free access to all parts of their farms and also for assistance in extricating the vehicle from river beds on several occasions.

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Miss.P. Eloff, who drafted most of the text figures as well as the geological map, must be especially thanked for her conscientious and capable assistance. Thanks are also due to Mrs. J. Elliott for typing of the final manuscript.

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II

REGIONAL GEOLOGICAL SETTING

The Waldau area is located, structurally, in what has become known as the central zone of the Damara Orogenic Belt. Gevers (1963) named this centrally situated linear, apparently geanticlinal area, the "Abbabis Swell" (Fig.1).

Smith (1965) summarised the work of early German investigators and described the geology of a large part of the main outcrop area of the Abbabis Swell situated south-west of the present area. Jacob (1974) studied a similarly large area to the south and south-east of Smith's mapping. This work largely covered the major and best exposed portion of the Abbabis Swell and led to the identification of the gross structural and stratigraphic characteristics of the zone.

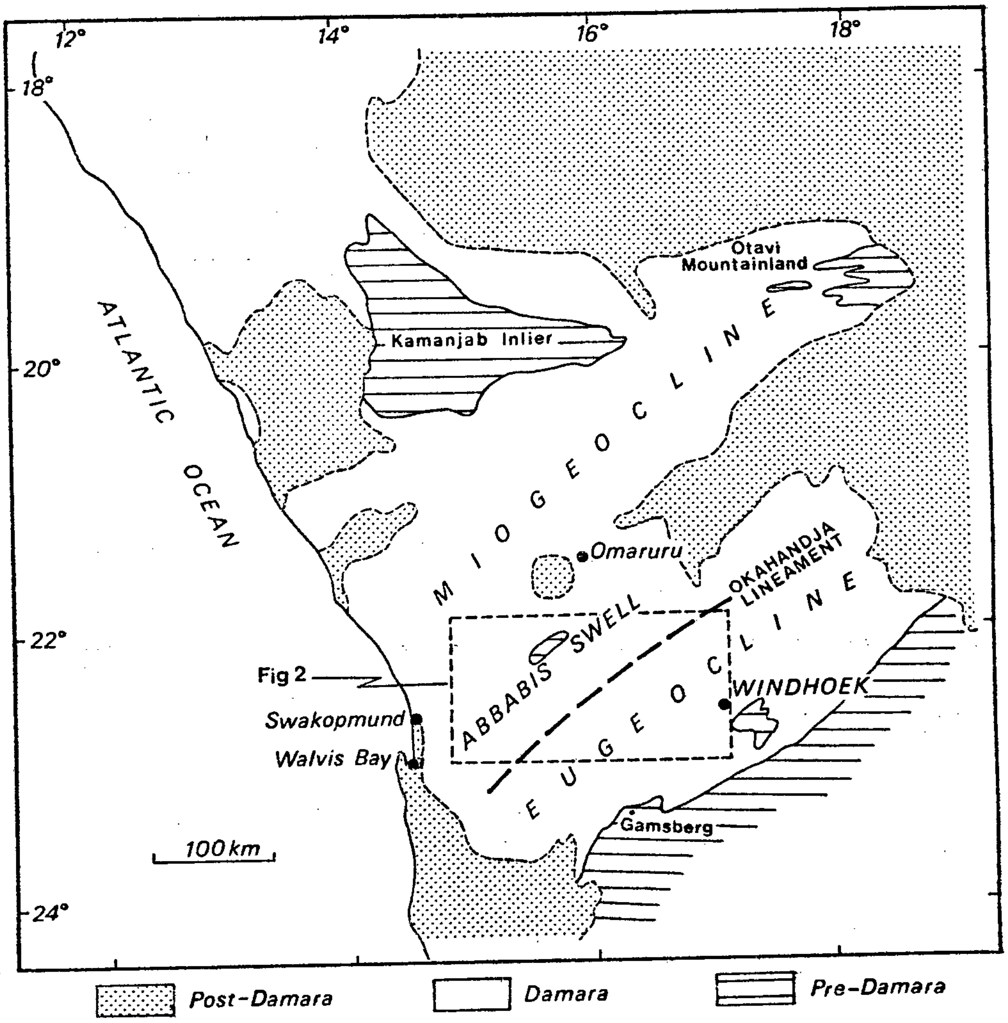


Fig.1. Location map of part of South West Africa showing places and features mentioned in the text.

The most recent stratigraphic terminology for the central zone, as submitted to the South African Committee for Stratigraphy (1976), is as yet unpublished.

Reference should also be made to Jacob (*op.cit.*) for the most recent published summary of stratigraphic terminology for the Damara Orogen and to Table 1 for comparisons of recent terminology with that to be used in this report.

Rocks correlated with the Etusis Formation of the Nosib Group in the Waldau area, make up the eastern-most known occurrences of this formation along the strike of the Abbabis Swell. The area is unique, in that it is separated from the last known outcrops of similar rocks to the west, by some 35 km between the area south of Wilhelmstal and Ozombanda (Fig.2). Regional investigations, as part of a mineral exploration program, have not disclosed any occurrences of possible Nosib equivalents to the east of Okahandja. Some outcrops of probably Nosib equivalents (well-bedded felspathic quartzites), occur in a small complex structure on the farm Okamongongua 15, some 6 km north of the most northerly outcrops of Nosib rocks on Waldau West 11. Another little known area of Nosib rocks occurs some 50 km to the south-west in the isolated "Lievenberg Dome" (Gevers, 1963 and Fig.2).

Marble bands, probably belonging to the Karibib Formation, occur in the area to the north-west, north and east as far as Okahandja and form sinuous bands enclosed in representatives of either the Kuiseb Formation, Salem or other granites.

It has become increasingly evident in recent years through the work of Gevers (*op.cit.*), Smith (1961, 1965) and Jacob (1974), that the geanticlinal Abbabis Swell was present as a positive feature from the earliest times in the Damara Geosyncline. This feature has apparently had a considerable influence on the distribution of sedimentation in the northern and southern parts of the geosyncline.

The type areas of many lower Damaran sequences in the central zone of the Damara Orogen (e.g. Etusis, Kahn, Dome Gorge, Chuos and Karibib Formations) are undoubtedly characteristic of fairly shallow-water sedimentation. The sequence there has, nevertheless, until quite recently been referred to as an eugeosynclinal accumulation (Martin, 1965; Jacob *op.cit.*).

In recent years, the significance of a marked change in tectonic style between the Abbabis Swell and the Khomas Trough and the possible nature and origin of this boundary have become increasingly important in the interpretation of the stratigraphic and tectonic history of the Damara Orogen.

Gevers (*op.cit.*), must be credited with the first published account of the possible existence of a major linear structure dividing the strongly contrasting tectonic styles of the Abbabis Swell and the Khomas Trough, which he termed the "infrastructure" and the "suprastructure" respectively.

Faupel (1974) alluded to the existence of a northward dipping thrust fault in the southward overturned limb of the Khomas "synclinorium" which acted as the locus for intrusion of the Donkerhoek Granite.

In the southeastern part of his area, Jacob (*op.cit.*) noted a marked

Table 1. Recent and current lithostratigraphic terminology for the Central zone of the Damara Orogen

Jacob (1974)			S.A.C.S. (1976)			Present Investigation			
Khan/Swakop area			Central and Western regions			Waldau area			
	Subgroup	Formation		Subgroup	Formation			Formation	
Damara Group	Khomas	Witpoort in west Tinkas in east	Swakop Group	Khomas	Kuiseb	Swakop Group		Kuiseb	DAMARA SUPERGROUP
		Tinkas in east Husab in west			Karibib			Karibib	
		Chuos			Chuos		not represented		
	Unconformity			Discordance					
		Rössing		Ugab	Dome Gorge				
Paraconformity/unconformity			Discordance			Paraconformity/unconformity			
Nosib Group		Khan	Nosib Group		Khan			Etusis	
		Etusis			Etusis				

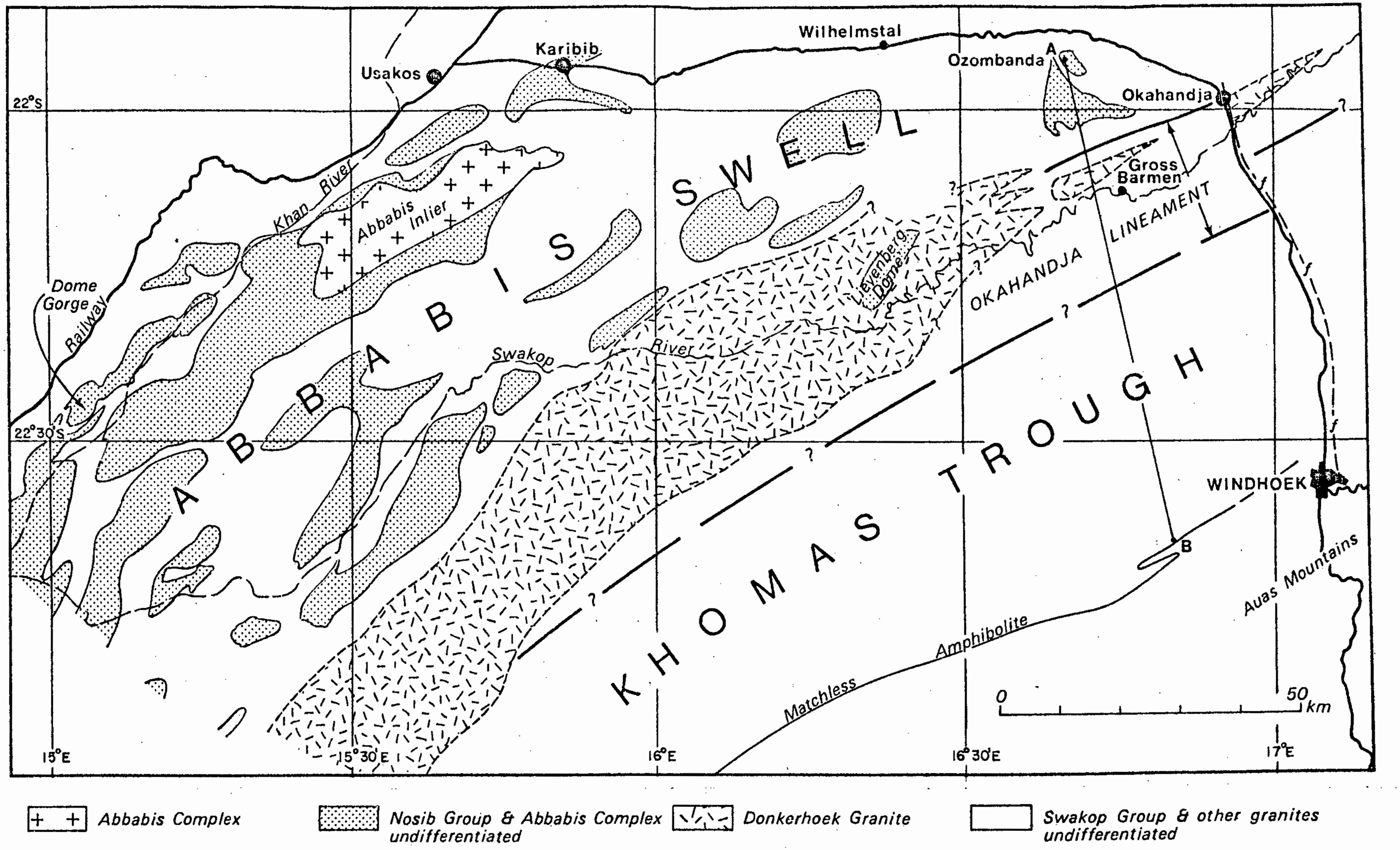


Fig.2. Generalised geological map of the central part of the Damara Orogenic Belt. Geology from Smith (1965), Jacob (1974) and photo-interpretation of ERTS-1 imagery. A-B = section line for Fig. 30.

change in style of deformation and he considered this at least partly due to a change in lithology in the Swakop Group. Smith (1965) similarly recorded a significant change in lithology in the lower portion of the Swakop Group (upper stage of Hakos Series) from predominantly calcareous (marbles) to predominantly pelitic along the south-west margin of his area (see map accompanying Smith (1965), farm Tsaobismund 85).

Miller (personal communication) recognised the existence of a marked aeromagnetic lineament, defined as the boundary between an area of high magnetic relief to the north and of low magnetic relief to the south, coinciding with the postulated position of the features mentioned above. This feature has been termed the "*Okahandja Lineament*" (Fig.2).

The linear nature of this feature and the possibility that it represents a line of fundamental weakness since early Damaran times - re-activated at later periods, throughout Damaran tectonic history - cannot be ignored.

The similarity between some of the characteristics of the Okahandja Lineament and those of the previously proposed boundary between the miogeosynclinal Outjo Facies and the supposedly eugeosynclinal, Swakop Facies (Martin, 1965) in the vicinity of the Abbabis Swell must be mentioned.

Miller (1972) recognised, in the area north of Omaruru, the existence of large normal faults forming a boundary between pre-Damara basement of the Kamanjab Inlier (Fig.1) to the north and Damaran rocks to the south. Movement along these faults which had been active since early Damaran times, continued to play a role in the distribution of sedimentation at least until lower Swakop times. This fault zone, Miller (*op.cit.*) recognised as being the locus of extrusion of large volumes of acid volcanic rocks (Naauwpoort Formation) forming the major part of the Nosib Group in this area.

Further east along the southern margin of the Otavi Mountain Land (Fig.1), originally andesitic lavas and pyroclastics of the Kombat Suid Formation (Smit, 1962) or, as they are now known, the Askevold Formation (Kröner, 1974), occupy a similar basal position overlying Nosib quartzite and pre-Damaran basement.

It must not be forgotten, however, that the north-east trending branch of the Damara Orogenic Belt is possibly a relatively minor part of a much larger Pan-African Orogenic belt, (Clifford, 1970) a major trunk of which extends along the west coast of Africa from Gabon to the Cape (Martin, 1965).

The situation of the Waldau area, in the zone of interplay between the Abbabis Swell and the Khomas Trough means that possibly important evidence exists in this area which reflects the tectonic evolution of the Okahandja Lineament and that it may well provide further clues to the origins of the Damaran Orogeny.

III

STRATIGRAPHY AND LITHOLOGY

A. Abbabis Complex

Ancient rocks of pre-Damaran age, making up the Abbabis Formation (Smith, 1965), are located in the large pre-Damaran inlier south of Usakos. The informal term Abbabis Complex has been applied more recently (Kröner, 1974) and will be used here. These rocks form the basement core of the Abbabis Swell.

As no formal sub-division of the Abbabis Complex has yet been proposed, the small areas of pre-Damaran rocks found elsewhere in this central zone of the orogen, have been included as part of the Abbabis Complex as a whole.

In the present area a sequence of metasedimentary and granitic rocks having markedly different lithology to the Etusis Formation overlying it and in other areas, is assigned to the Abbabis Complex. These rocks are located in the cores of both the Waldau West and Waldau Ridge structures (Fig.3). The granitic members weather easily and are poorly exposed while the metasediments, although outcropping, usually occur as piles of loose boulders.

1. Gneiss, granite and pegmatite (*Ab1*)

The majority of granitic rocks belonging to the Abbabis Complex in this area are very well-foliated, medium-grained, leucocratic or biotite-rich gneissic rocks, commonly containing migmatitic remnants of biotite schist. In the north on Waldau West, the gneissic rocks grade into more homogeneous, coarser-grained and in parts pegmatitic, reddish leucocratic granitic material. This in turn merges with the quartzo-felspathic gneisses of the Etusis Formation. These are probably equivalent to portions of the younger reddish granite (G5). Only rarely were small patches of red augen-gneiss, such as described by Smith (1965) and Jacob (1974) from the Khan-Swakop area, seen in the present area.

On Waldau West the foliation tends to be largely conformable between these rocks and those of the associated metasediments and the overlying Etusis Formation. In the core of the Waldau Ridge structure the gneissic rocks are more extensively sheared, undoubtedly due to Damaran deformation.

Smith (*op.cit.*) reported general conformity of foliation in the Abbabis gneiss and Nosib Group along the contacts. It should not be unexpected that Damaran deformation made a significant imprint on the pre-Damaran rocks and in the larger inliers the effects may be confined to contact zones while in the smaller inliers such as that described here, the effects are more penetrative.

A variety of leucocratic, pegmatitic and aplitic rocks occur intruding gneissic and metasedimentary members. Many of these are unfoliated and may be

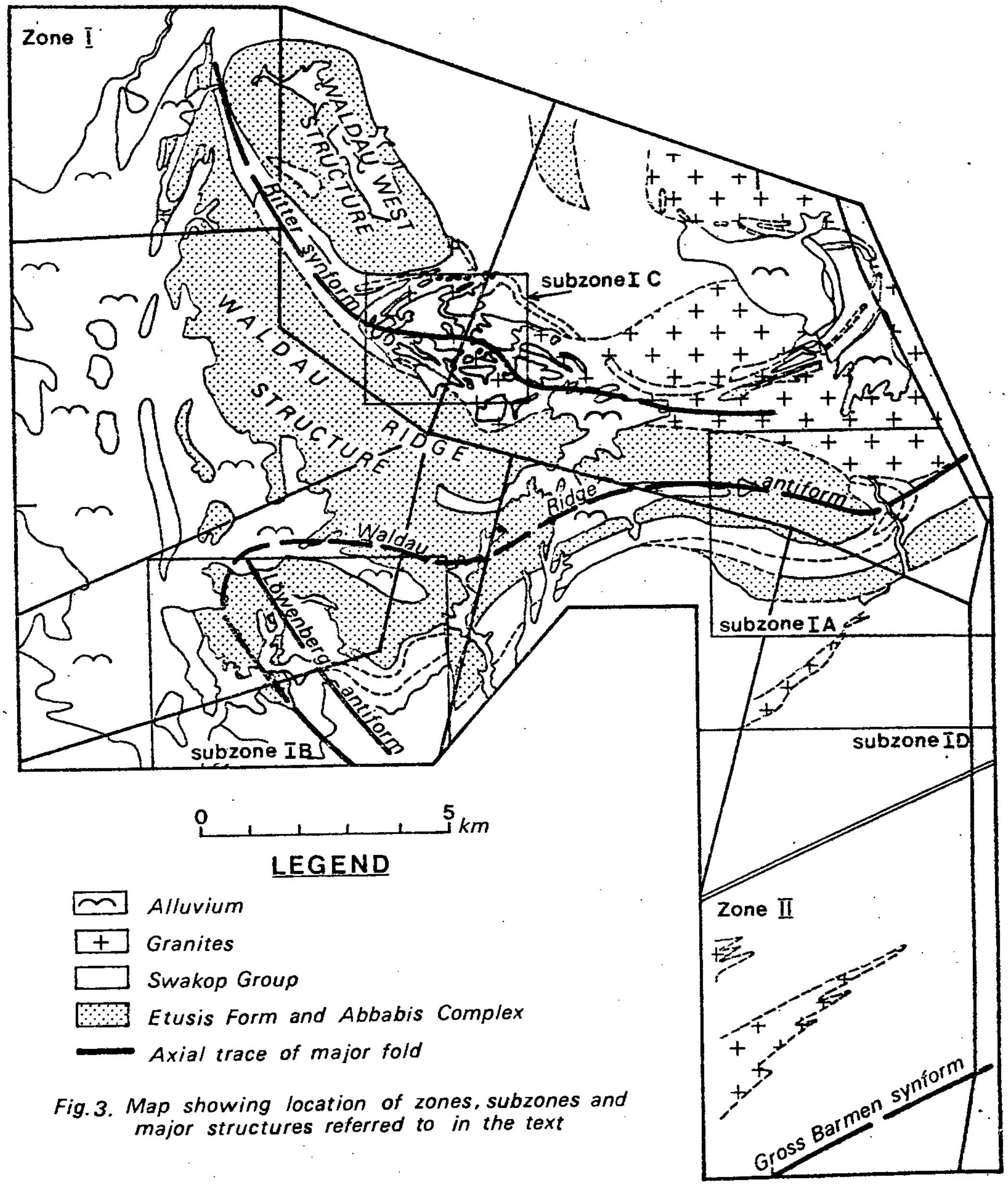


Fig. 3. Map showing location of zones, subzones and major structures referred to in the text

related to the Damaran Orogeny, yet they do not intrude the overlying, more massive Etusis Formation rocks.

2. Metasediments (*Ab2*)

The pre-Damaran metasediments are those most characteristically different from the overlying Etusis Formation. Varieties of highly recrystallised quartzitic rocks containing varying amounts of calc-silicate minerals are commonly found. These are classed as metaquartzites (Gary *et. al.*, 1972). "Pure metaquartzites" (>95 per cent quartz) and "impure metaquartzites" (80-95 per cent quartz) were not distinguished.

In hand specimens, quartz-rich bands alternate with bands containing linear segregations of fine-grained, largely greenish minerals. In thin sections the calc-silicate minerals are seen to be predominantly diopside with lesser amounts of almost colourless amphibole as well as minor plagioclase and accessory minerals. Textures are characteristically granoblastic, both equigranular and inequigranular with polygonal and interlobate grain boundaries in the quartz-rich bands, which are much coarser-grained than those formed by other minerals. Calc-silicate minerals are usually fine-grained equigranular, idiomorphic to sub-idiomorphic in the segregations and the texture commonly decussate.

Although there is some similarity in mineralogy between these rocks and some of those of the Karibib Formation, the textural differences are significant. Textures in the Abbabis metasediments perhaps indicate a more intense period of high-grade metamorphism prior to the Damaran episode, or the effects of two high-grade events, one of which was pre-Damaran.

Minor rock types associated with these quartzitic types are coarse-grained calc-silicate segregations consisting often of only diopside. A fairly narrow band of either fine or medium-grained, impure marble occurs at the top of the sequence.

One small occurrence of conglomeratic rocks, occurs on the north side of the small inlier of Abbabis rocks found on the eastern side of Elbe (4D). The relationship of this occurrence to the other rocks is not known as it is surrounded by alluvium. Pebbles and cobbles in the rock are predominantly granitic in composition, while the matrix appears to be similar to the composition of the metaquartzites described above. The rock is strongly deformed and the linear fabric being nearly horizontal.

The strike of the main area of Abbabis metasedimentary rocks on Waldau West, is slightly oblique to the contact with the Nosib Group, along the southwestern side of the Waldau West structure.

Smith (1965) described a sequence of calc-silicate rocks and marbles folded within the granitic rocks of the Abbabis Complex, south of Usakos. It could be suggested that these rocks underlying the Etusis Formation in the present area should be correlated with those described by Smith (*op.cit.*).

B. Etusis Formation (Nosib Group)

The rocks assigned to the Etusis Formation, are characteristically a sequence dominated by an abundance of quartzo-felspathic rocks. Pelitic schists form a relatively minor part of the sequence and are found at the base or interlayered with felspathic quartzite at the top. These rocks underlie most of the area of the Waldau Ridge structure and rim the main outcrop area of Abbabis Complex rocks in the Waldau West structure.

1. Lower schist member (*NslS*)

The base of the Etusis Formation along the Waldau Ridge in the east, (5G, 5H) is characterised by a conspicuous horizon of sillimanite-biotite schist reaching a maximum thickness of 40 metres in this area. Sillimanite forms ovoid clusters of fibrolite, showing marked alteration to white mica. The exact contact with the underlying Abbabis rocks is obscured by scree and no trace of a basal conglomerate was found.

This lowermost member is not exposed in the Waldau West structure excepting for a narrow strip of low relief north of the iron-rich horizon possibly indicating the position of this member.

Smith (1965) described a biotite schist and in part a biotite-sillimanite gneiss locally underlying the basal conglomerate of the Etusis Formation in the Khan-Swakop area, which he thought might belong to the Abbabis Complex. In the present area, this particular schist unit is very clearly part of the Etusis Formation and on Waldau is separated from the Abbabis metasediments by a zone of sheared Abbabis gneiss.

2. Main gneissic member (*NsGn1, NsGn2*)

The lithology of the Etusis Formation in the Waldau area is dominated by the reddish to yellowish weathering, leucocratic, biotite-microcline gneisses forming the highest parts of the area along the Waldau Ridge. In general these rocks are medium-grained and have the appearance of granitic gneisses. Hand specimens contain easily recognisable pink K-felspar, quartz and biotite. The rocks, apparently very homogeneous with regard to composition, colour and grain size, are largely recrystallised to a granitic texture.

In the northern part of the Waldau Ridge structure, the *NsGn2* unit is the dominant rock type. The foliation is extensively disrupted by rheomorphic veining, migmatite and locally, the development of even-grained, unfoliated, reddish granite. Weak K-felspar blastesis is developed in some of the rocks in the southern parts of this unit.

These gneissic rocks are characterised, in thin section, by a granoblastic texture and an abundance of microcline felspar commonly exceeding 40 per cent of the rock by volume. Na and K-felspars were distinguished by selective staining (Bailey and Stevens, 1960). Na-felspars are also abundant to the extent that combined alkali felspars often exceed 60 per cent of the rock by volume. Plagioclase is usually present in minor amounts, although a few samples contain between 20 and 40 per cent by volume. Indications from a few optical analyses are that the composition of these plagioclases is in the olioclase range with biotite a minor constituent, rarely exceeding 3 per cent by volume. Granular ore and zircon are common accessory minerals. Quartz often occurs as rounded exsolutions in K-felspars. Modal compositions of most of the rocks on which point-count determinations were made are in the range of alkali-felspar granite (Fig.4)

There appears to be a coarse compositional layering in this member of the formation and is expressed as a transgressive zone containing a concentration of quartz-sillimanite nodules, over- and underlain by nodule-free gneiss. This zone, locally attaining a maximum thickness of some 150 m, (tectonic thickening) on Waldau (5I), appears to pinch out towards the north-west against the contact with the upper schist and quartzite member, while on the south side of the Waldau Ridge, the relationship is less clear. In the west on Ombujongupa Süd (7C), a thin zone of nodular gneiss in the order of 10 to 20 m thick, directly underlies the uppermost member.

A significant layer of iron-rich sillimanite gneiss occurs at the base of the Etusis Formation along the south-west side of the Waldau West structure. It was not possible to determine the exact thickenss due to poor exposure, but it may be up to 30 m thick.

One typical exposure of this rock type contains largely quartz and K-felspar (54 and 31 per cent respectively), the remainder being made up of fibrolite, biotite (8 per cent) and disseminated granular ore (± 7 per cent).

A narrow layer of an unusual minor rock type was found associated with the iron-rich gneisses consisting of approximately equal proportions of quartz and microcline, occasionally with plagioclase and slightly less than 10 per cent of fine-grained euhedral ore, which in hand specimens could be recognised as pyrrhotite.

It is possible therefore, that much of the iron staining seen in this layer may be due to the weathering of significant amounts of disseminated iron sulphide. Towards the west as far as the Löwen River (2C) this iron-rich layer is encountered. In the Leoparden River (2C) the iron-rich layer is found continuously, from the basal contact with the Abbabis Complex, throughout a narrow section of *NsGn2*, to underly the Swakop Group in the north-western part of the Ritter synform (Fig. 3). Ferruginuous, migmatitic, quartzo-felspathic gneiss re-appears in the Leoparden River to the west of the Ritter synform and is found discontinuously along the western side of the Waldau Ridge structure in the upper part of the Etusis Formation.

Geochemical analyses of soil samples, collected as part of a mineral exploration program, revealed that this iron-rich layer is weakly cupriferous with values of up to four times back-ground in the soil associated with it (unpublished report).

Another important layer of iron-rich rocks was found on the southern part of Waldau West near the Elbe boundary (4D). The rocks of the area are not well exposed at the base of the Hohlenberg and outcrops of banded magnetite quartzite (<4 m thick) occur discontinuously for a strike length of some 700 m along the base of the ridge. Towards the western end of the outcrops this layer grades into thin-banded, pink, felspathic quartzite containing disseminated magnetite. The banded magnetite quartzite layer thins rapidly to approximately 1 m thick and towards the east of the main exposure the layer thins rapidly and disappears.

At the extreme western end a thin layer (1,5 m) of metaquartzite containing disseminated pyrrhotite, occurs in all respects identical to that found further north in the base of the Etusis Formation. This sequence is overlain by massive, weakly foliated, reddish granitic gneiss (*NsGn2*). Further south, close to the uppermost contact of this member in the hinge of the Löwenberg antiform (6D; Fig.3), a narrow layer of iron-rich sillimanite gneiss is found, practically identical to the layer on Waldau West, occurring there at the base of the Etusis Formation.

Disseminated magnetite has been found in the uppermost parts of the member (*NsGn1*) on Löwenberg hill (7D) as well as in the zone of probable acid volcanic rocks (*NsV*), occupying the same stratigraphic position on Otjiruse (7E). These rocks, probably acid volcanics, are fine to medium-grained and are well foliated. The rock consists of a fine-grained quartzo-felspathic, granoblastic matrix in which rounded and elongated, largely polygonised blasto-porphyritic quartz and microcline occur, together with the scattered euhedral blasto-porphyritic crystals of magnetite. Some magnetite quartzite rubble was found in the same area.

In the eastern part of the Waldau Ridge (6I), a narrow layer (1-2 m) of white felspathic quartzite containing disseminated pyrrhotite, much the same as that found to the west in two places on Waldau West, was found immediately overlying the nodular sillimanite gneiss unit.

3. Upper schist and quartzite member (*NsuS + Q*)

The uppermost member of the Etusis Formation in this area is made up of predominantly pelitic rocks in the lower part and a predominantly quartzitic upper part. This member is best developed along the southern margin of the Waldau Ridge structure in the Löwenberg antiform and in the eastern hinge of the Waldau Ridge antiform (5H, 5I, 6H, 6I; Fig.3). Occasional felspathic quartzites are found interlayered with the upper parts of the underlying reddish granitic gneiss (*NsGn2*) in the south-eastern part of the Waldau West structure. Iron-rich felspathic quartzites underlie the Swakop group in the Leoparden River on the east side of the Ritter synform, while thinly layered felspathic quartzites underlie the Swakop group in the Leoparden River on the east side of the Ritter synform, while thinly layered felspathic quartzites increase in proportion, upwards in the sequence so that the uppermost section is devoid of interlayered schists. The schists here are practically identical to the lowermost biotite-sillimanite schist member of the Etusis Formation and the interlayered felspathic quartzites usually contain quartz-sillimanite nodules.

On northern Gross Barmen (61) a narrow, discontinuous layer of amphibole schist occurs in the core of the belt of upper Etusis Formation rocks to the south of the Waldau Ridge. The rocks in this belt are significantly more schistose and quartzite layers are thinner. In the absence of the quartz-amphibole unit, marking the base of the Swakop Group everywhere, the uppermost contact here would be difficult to establish. This upper member apparently pinches out between the main gneiss member and the base of the Swakop Group on the north side of the Waldau Ridge (5G) and in the west on the Elbe (5C).

C. Swakop Group

As noted elsewhere in the region (Jacob, 1974; Smith, 1965)there is also a significant difference in lithology in the Waldau area, between the predominantly quartzo-felspathic Etusis Formation and the predominantly carbonate and pelitic association of the Swakop Group.

In the same area, the lowermost representatives (Dome Gorge and Chuos Formations) of the Swakop Group do not occur (Table 1). Both Smith (*op.cit.*) and Jacob (*op.cit.*) noted the variability in lithotype and thickness of the Dome Gorge Formation (lower stage of Hakos series of Smith, *op.cit.*; Rossing Formation of Jacob, *op.cit.*). The restricted distribution of this unit, together with that of the Chuos Formation (middle or Chuos stage of Hakos series of Smith, *op.cit.*) is noted by both workers. The area of occurrence of these formations is largely on the north-west side of the main Abbabis inlier.

1. Karibib Formation (*Sw1C*)

In the absence of the Chuos Formation, and with the known restricted distribution of the Dome Gorge Formation, the relatively thin sequence of calc-quartzites, calc-granofelses and marbles developed in the Waldau area, have been assigned to the Karibib Formation as this is the most extensive sequence of carbonate rocks developed in the Swakop Group in the environs of the Abbabis Swell.

There appears to be a regional angular unconformity between the Etusis Formation and the Karibib Formation. In the Waldau area, the basal unit of the sequence is a characteristic blue-black or black coloured, quartz-amphibole gneiss or schist, which appears everywhere marking the contact between the Etusis Formation and the Swakop Group. Transgression can be clearly seen on the north side of the Waldau Ridge (5G, 5H), where three units of the Etusis Formation (the nodular sillimanite gneiss unit, the upper gneiss unit and the upper schist and quartzite member) are cut off by the contact which could not be seen in the field due to the presence of granite intrusion. Similar transgression is less clearly evident in the west (5C, 6C) due to poor exposure. In the Waldau West structure it is apparent that this formation transgresses onto the Abbabis Complex (2D). The characteristic basal unit is found in the core of the structure, in an area of poor exposure and of intense deformation. Thick-banded, coarse-grained, grey marble and biotite schist, characteristic of the upper part of the Karibib Formation occur in this vicinity as well and are in direct contact with the Abbabis gneiss.

A further indication of the transgressive nature of the contact, is believed to be the sporadic development of patchy, cupriferous horizons in the lower unit of the Karibib Formation on Ombujongupa Süd (7C) and Otjiruse (7E). The apparent evidence for an angular unconformity between the Etusis Formation and the Swakop Group means that the weakly cupriferous, iron-rich unit on Waldau West was probably exposed at the time when the Karibib Formation was deposited and possibly resulted in the local concentration of copper derived from the exposed Etusis beds.

The greatest thickness of the Karibib Formation may be present in the Ritter synform (4E, 4F) where a significant amount of calc-quartzite occurs between the basal quartz-amphibole gneiss and the marble and calc-granofels layers of the upper part. Complex deformation in this area makes calculation of true thickness impossible. Similar lithologies occur in the structure which builds the Waldauberg (3I, 4I).

Significant thicknesses of the Karibib Formation in this area are developed around the western and southern rim of the Waldau Ridge structure where the basal quartz-amphibole gneiss is followed by thinly banded calc-granofels and occasional amphibole schist, followed by interlayered, thin calc-granofels and marble. The thickness of marble bands increases going up in the sequence and they become interlayered with biotite and biotite-amphibole schist. The facies change from calcareous to pelitic sequences occurs over a very short distance as shown by the belt of Karibib Formation rocks south of the Waldau Ridge on Waldau and Gross Barmen (6I, 6J, 5J). The northern limb of this fold consists solely of carbonate-rich rocks which become thinner and grade into pelitic rocks progressing northwards around the eastern hinge of the Waldau Ridge antiform. The south limb of this fold contains only pelitic types with thin calc-granofels layers. Regardless of this facies change, the contact with the underlying Etusis Formation rocks on either side is marked by the prominent dark coloured, quartz-amphibole gneiss unit.

The maximum thickness of the Karibib Formation in the Waldau area is estimated to be of the order of 150-200 m. The southern contact of the belt of Etusis rocks on northern Gross Barmen is marked by a quartz-amphibole schist unit which is tectonically interlayered with felspathic quartzite bands in part. Calcareous rocks are lacking south of this contact, except for a few thin bands of fine-grained, white marble, interlayered with biotite schist some 0,5 and 2,3 km south of this contact. The position of these marble bands high up in the pelitic sequence may be due to tectonic, rather than stratigraphic layering.

Smith (1965) depicted his upper Hakos stage (Karibib Formation) as showing a regional transition from massive marbles in the Karibib area to the north, to a sequence predominated by pelitic schists towards the south. Jacob (1974) proposed a lithostratigraphic sub-division for the same transition from predominantly carbonate-rich, Husab Formation in the west, to the more pelitic Tinkas Formation in the east (Table 1).

2. Kuiseb Formation (*Sw2S*)

Regionally, the predominantly pelitic Kuiseb Formation, which is the equivalent of Smith's (1965) Khomas series, must be recognised as, in part, the chronostratigraphic equivalent of the Karibib Formation.

The Kuiseb Formation lithotypes are best developed to the south of the Waldau Ridge structure and to the east outside the mapped area, towards Okahandja. In the northern and western parts of the area the position of this unit has largely been taken up by the Salem Granite - widely accepted as being largely the product of ultrametamorphism of these rocks (Martin, 1965; Smith, 1965; Miller, 1973; Jacob, 1974).

The Kuiseb Formation where best exposed on Gross Barmen is characterised by quartz-biotite schist, biotite schist, sillimanite-biotite schists, cordierite-biotite schist, andalusite-biotite schist and quartz-amphibole schist. Thin calc-granofels layers occur in the vicinity of the quartz-amphibole schist, together with thin quartzite layers. Rarely developed K-felspar porphyroblasts were found in the northern part of Gross Barmen as well as to the north of the Waldau Ridge.

In the vicinity of the Gross Barmen hot springs, calc-granofels layers have been deformed into elongate, boudin-like, spindle-shaped bodies, described by Gevers (1963) as "pyroxene-amphibole-garnet-granulites". Porada (1973) reported the occurrence of similar bodies in different forms throughout the Khomas Trough and proposed that a broad two-fold lithologic sub-division of the Khomas series (Kuiseb Formation) could be made on the basis of the occurrence of the calc-granofels bodies, recognised as being concentrated in the lowermost parts of the Khomas series.

On Elbe and Ombujongupa Süd(4B, 6A, 6B) a unique lithologic unit occurs in association with significant concentrations of massive, semi-massive and disseminated sulphides rich in iron, copper and zinc (unpublished reports). The host rock of this base-metal concentration is a garnet-bearing felspathic quartzite. With the exception of the garnet this rock is very similar in composition to the pyrrhotite-bearing, felspathic quartzites found in the Etusis Formation.

D. Igneous Rocks

Most previous descriptions in the central zone of the Damara Belt have drawn attention to the remarkable association of certain wide-spread granitic rocks with particular stratigraphic levels (Smith, 1965 and Jacob, 1974).

Red Granite-Gneiss is the sack-name which has been applied by Jacob (*op. cit.*) to a variety of gneissic-granites and granite gneisses, generally red in colour and located stratigraphically below the Karibib Formation (Husab Formation of Jacob).

Because there is some doubt, in the areas mapped by Smith (*op.cit.*) and Jacob (*op.cit.*) about the origin of these rocks described by Jacob as Red Granite-Gneiss and because there are undoubtedly some rocks in this group which are pre-Damaran as well as anatectic equivalents of the Etusis Formation, they were described by these workers as separate from the Nosib Group.

Rocks, which on the basis of descriptions given by both Smith and Jacob can be correlated with some lithotypes in the Red Granite-Gneiss, have been described as *NsGn2* in the Waldau area. *NsGn2* can be fairly readily distinguished from granitic rocks of the Abbabis Complex in this area and has been described as a member of the Etusis Formation.

1. Salem Granite (*Sw2Gn*)

Salem granite is a sack name which has been expanded from the earliest definition of the rocks in the type area originally described by Gürich (Gevers, 1931), to include a variety of granitic rocks occupying the stratigraphic position of the Kuiseb Formation (Khomas Series of Smith).

A biotite-rich, porphyroblastic gneissic-granite is the local representative of the Salem Granite in the Waldau area.

On Waldau, representatives of the Salem Granite have the general appearance of a medium-grained, porphyroblastic paragneiss grading rapidly into pelitic Kuiseb schists with reduction in the amount of K-felspar porphyroblasts. Some parts, however, chiefly in the north, grade into masses of inhomogeneous diatexite (Mehnert, 1968), consisting of partially digested inclusions of metatectic paragneiss and schlieren which are contorted around them. Relict foliation and schlieren in this area are nevertheless generally conformable with the regional trend of nearby metasediments.

Other areas on Waldau (3G) show patchy and irregular venetic neosomes, displaying pinch-and-swell structure, criss-crossing well-foliated paleosome exhibiting extensive quartzo-felspathic blastesis.

At the Osombanda River waterfall (1C, 1B) more homogeneous Salem Granite is, to a large extent, a coarse-grained, porphyritic, biotite granite-gneiss. Phenocrysts (1-3 cm) of alkali-felspar show various orientations although they generally conform to the larger scale foliation. The felspar phenocrysts are commonly characterised by pink, K-rich cores, surrounded by white Na-rich rims. Other quartzo-felspathic segregations, generally Na-rich, form irregular lensoid masses, the coarse biotite foliation being wedged between or wrapped around them.

The foliation in the Salem Granite is everywhere regionally concordant with nearby metasediments and is generally better developed near to regional contacts. Actual contacts between the Salem Granite and metasediments are rarely seen, particularly in the west. Where they are found the contacts are concordant and sharp, with marble and calc-granofels layers, but generally concordant and gradational with the schists. No contact metamorphic effects were seen which could be related to the Salem Granite. Point counts were conducted on the few suitable thin sections available and the modal compositions are represented in Fig. 4.

2. Orthopyroxene-bearing Gabbroic Rock (*B*).

Along the southern margin of the flat sandy area on Waldau, underlain largely by Salem Granite, sporadic outcrops of dark coloured medium and coarse-grained mafic rock occur. Although no continuity can be postulated from surface exposures, the area is characterised by essentially darker tones on aerial photographs. The limits of the body were defined on this basis.

Three varieties are distinguished on field characteristics, mainly grain size and foliation.

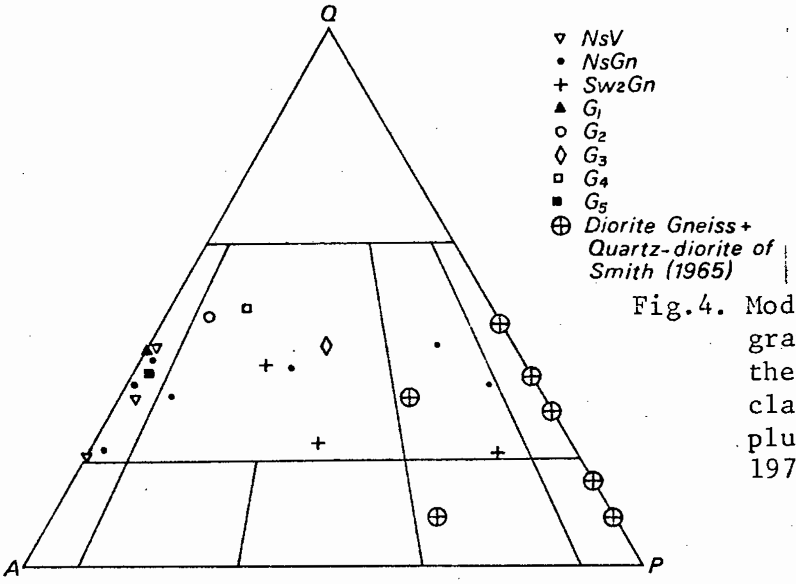


Fig.4. Modal compositions of various granitic rocks referred to in the text, plotted on the classification diagram for plutonic rocks (Streckeisen, 1974)

The fine-grained, slightly porphyritic variety is fresh and contains no trace of foliation. Both ortho- and clinopyroxene are present in approximately equal amounts as small, (0,5-1 mm) subhedral phenocrysts as well as anhedral crystals in the ground mass. Commonly, the clinopyroxene (augite) is seen to mantle the orthopyroxene and the pyroxenes are clouded by minute alterations (uralitisation). Plagioclase is fresh and shows some zoning with compositions between labrodorite and bytownite (determined by the Michel-Levy method, Kerr, 1959).

The other two types are medium-grained and essentially similar in the hand specimen, except that one is weakly foliated. The foliated variety seems to occur closer to the margins of the body. The unfoliated member of this pair displays extensive alteration of clinopyroxene to pale-green-brown amphibole in xenoblastic crystals as well as containing many smaller sub-idiomorphic and idiomorphic amphibole crystals of similar colour.

In the more foliated variety, the clinopyroxene is replaced by darker, green-brown amphibole. No orthopyroxene was observed in these two specimens and in both, large, sub-idioblastic, brown biotite partly encloses the xenoblastic amphiboles. Plagioclase occurs as unoriented subhedral laths, commonly with myrmeketic intergrowths and compositions in the labrodorite range. These varieties thus appear to be gabbroic in character, with some members containing orthopyroxene.

Regionally, this rock type has contacts which are conformable with the metasediments to the south. Locally, contacts are obscured by alluvium. The body appears to have intruded the G2 granite, an observation based on one poor exposure where a small dyke of mafic rock is found to trend across the weak foliation trend in the G2 granite. The body is cut by a number of narrow dykes and veins of pink aplitic granite.

A narrow (5-10 m wide) apparently continuous zone of granodioritic rock occurs along the north-east side of the Waldau West structure, approximately 150-200 m east of the thin discontinuous carbonate horizons. Hornblende is fresh and green-brown in colour, sometimes poikiloblastically enclosing quartz in xenoblastic crystals, but the majority occur as oriented sub-idiomorphic crystals of similar colour. Plagioclase is the major light-coloured constituent, associated with lesser amounts of quartz and alkali felspar. It is not conclusive whether this rock type belongs to the larger mafic body or whether it is a minor variety of the Salem Suite.

Smith (1965) has described large bodies of igneous rock generally more mafic than the Salem Granite as quartz-diorite and diorite gneiss. Recalculation of Smith's analyses for plotting on the triangular diagram for plutonic rocks (Streckeisen, 1974)shows that these rocks are largely tonalites, but some of them correspond to quartz-diorites, quartz monzodiorite and granodiorite (Fig.4).

The most likely correlates of the body of basic rock on Waldau are possibly small isolated bodies of "uralitised gabbro" which Smith (*op.cit.*) described as intruding the quartz diorite, but possibly being differentiates from deep-seated portions of the same magma.

To comment in depth on the origins of this rock type is beyond the scope of this study. It seems likely that the origin of such a rock type is quite fundamental and unlikely that it is a residual differentiate of material related to the Salem Granite Suite.

3. *G1* Granite

This group forms a well-defined zone in the south-eastern part of Waldau and consists of a number of relatively narrow bands (10 cm to 5 m wide), interleaved with pelitic schists of the Kuiseb Formation extending over a width of some 200 m, where they occur most densely. Occasional narrower bands are found to the north and south over a total width of some 600 m. Occasional bands of a similar rock type are found conformably intruding the Karibib Formation on Ombujongupa Süd and the Abbabis Complex on Waldau West. On Gross Barmen a number of narrow bands, (less than 3 m wide) of possibly similar rock type, can be seen in the pelitic rocks of the Kuiseb Formation.

Locally, these dyke-like bodies are conformable with the major foliation in the south-east of Waldau and on Gross Barmen. On Waldau a macroscopic cross-cutting relationship exists with the major lithological contacts, but it has not been found to intrude the more homogeneous rocks of the Etusis Formation. Detailed examination of contacts indicate that these bodies predate s_2 on Waldau,as quartz-sillimanite nodules developed in this rock are flattened parallel to s_2. In general the rocks are fine-grained and consist largely of approximately equal proportions of granoblastic quartz and K-felspar (Fig.4), some of which appear to be blasto-porphyritic. Biotite and muscovite occur as small,scattered,orientated sub-idioblastic flakes, while small sub-idioblastic garnet crystals are an accessory constituent.

Gevers (1963) referred to similar rocks on Gross Barmen as "sillimanite-bearing aplites" and then concluded on examining them under the microscope that the felspar content was too low and that they were felspathic quartzites. He conceded that other bodies of similar rocks in the Waldau river represent "intrusive sheets of sugary aplite, and that their sillimanite content and highly sheared nature indicated an early stage of injection prior to the last intense phase of tectonism" (Gevers, *op.cit.*, p.219).

The present investigation of the main swarm of this rock type on Waldau has disclosed probably relict igneous features in the form of blasto-porphyritic quartz and K-felspar in a fine-grained groundmass made up solely of quartz and K-felspar. The lack of gradational contacts with the surrounding schists and the macroscopic transgressive nature of the bodies indicate that the rocks may represent a swarm of quartz and felspar-porphyry dykes intruded early in the deformational history of the area.

4. *G2* Granite

This rock type is found solely in the area north of the Waldau Ridge, in the Ritter synform and to some extent north and east of the Waldauberg (2H, 2I, 3J). Apart from the numerous dykes in the eastern part of the Ritter synform, it forms at least two main stock-like bodies; one largely in sub-zone I.C. and a larger body of more variable composition in the north-east of the mapped area (2H). A much smaller body of similar rock intrudes the Salem Granite in the vicinity of the Waldau West farmhouse (1E). Where interleaved with schistose rocks the dyke-like bodies are largely conformable (5H,5I).

This granite displays discordant and cross-cutting relationships with all other rocks in the Ritter synform as well as the G1 dykes in the east. Locally along the northern side of the Waldau Ridge (5F) and in the south-east of the Waldau West structure (3E), it intrudes the uppermost portions of the Etusis Formation. G2 granite is in turn apparently intruded by the basic body (*B*) as described previously.

Metasediments have hardly been disturbed by the intrusion of this granite, as evidenced particularly in sub-zone I.C., where the structural relationships were studied in detail. No contact metamorphic effects were noticed.

The rock is medium-grained and leucocratic, containing only minor amounts of biotite. A weak foliation is evident in areas where the rock is massive and not dyke-like. Microscopically, the specimens examined consist predominantly of granoblastic quartz and alkali-felspar which is largely microcline. Plagioclase is a minor constituent and is characterised by the development of albite rims in contact with alkali felspar (Fig.4). Small xenoblastic clusters of garnet are accessory minerals. Garnet segregations up to 2 cm in diameter are more common in the small body near the Waldau West farmhouse and in the north-east on Waldau.

The imprinted weak foliation in this rock indicates that it was intruded during the deformation, which gave rise to the development of the Ritter synform.

5. *G3* Granite

This rock group is very similar in the hand specimen to *G2*, being leucocratic and medium-grained and has been distinguished from *G2* largely on structural grounds. The main area of occurrence is in the west and south-west where numerous leucocratic granitic dykes are located along north-east trending fault and fracture planes. They intrude all members of the Damara Supergroup except for the more homogeneous rocks of the Etusis Formation. On Ombujongupa Süd, Elbe and Osombanda, the Kuiseb Formation schists are extensively intruded by irregular bodies of homogeneous, leucocratic and pegmatitic granite to form migmatites. The poorly exposed areas in the sand-filled valley of the Osombanda River are characterised by leucocratic, granitic scree. Drilling operations and underground development in this vicinity has shown the true nature of the bed rock to be that described above.

In sub-zone I.C. similar material fills north-east trending faults and fractures, which cut the *G2* granite and the Karibib Formation. In the east of the main area a few north-east trending dykes of leucocratic pegmatitic granite occur.

Specimens of dyke rocks examined in thin section are fine to medium-grained, with an apilitic texture. Plagioclase displays albite rims in contact with alkali-felspar and most felspars are extensively altered with biotite and muscovite as a very minor constituent (Fig.4).

Intrusion of this rock group post-dates the major tectonic activity in Zone I, as it fills north-east trending fault planes and is not disrupted.

6. *G4* Granite

Bodies of granitic rock assigned to this group occur on Elbe as small (30-40 m diameter) "castle-koppies" protruding above the sand-filled Osombanda River valley. On Osombanda, numerous veins of *G4* intrude Salem Granite in agmatitic fashion. In the extreme north of the area on Waldau West, larger masses of this rock type containing large isolated xenoliths of Salem Granite, intrude the quartzo-felspathic gneisses of the Etusis Formation to form agmatitic structures on a large scale. Contacts with the country rock are sharp and very minor, or no chilling effects are seen. At the Osombanda River waterfall below the main road, *G4* granite, occurs as veins in xenoliths of Salem Granite, in *G5*.

In hand specimen the rock is fine-grained, mesocratic, grey in colour and occasionally porphyritic (phenocrysts up to 0,5 cm). In thin section, microcline and orthoclase predominate over plagioclase which commonly displays albite rims, in contact with alkali-felspar. Biotite is a minor mafic constituent and some muscovite occurs apparently as an alteration of felspar (Fig. 4). Garnet forms scattered porphyroblastic aggregates up to 2 cm diameter, surrounded by quartzo-felspathic diffusion coronas. The coronas are deficient in biotite when compared to the surrounding rock, while the garnet shows some concentration of biotite. Differentiation of this type takes place *in situ* and the garnet is not a relict of a pre-intrusion metamorphic event (Jackson, 1976, p.95).

The *G4* granite definitely post-dates the latest tectonic event and had largely solidified prior to the intrusion of G5. The major area of occurrence appears to be north of the mapped area with minor apophyses as small stocks occurring to the south.

7. *G5* Granite

This characteristically reddish granitic rock type is probably only second in area of extent, to the Salem Granite. It is known to underlie large tracts of country to the north-west and west of the area mapped and forms all the prominent hills in these regions, as well as low exfoliating, whale-back outcrops. Contact relationships are best exposed at the Osombanda River waterfall below the main road. Agmatitic structures are developed with both xenoliths of Salem Granite and *G4* granite, while many nebulitic schlieren of fine-grained grey granitic material occur in *G5* at this site which may be partially absorbed remnants of *G4*. Narrow pegmatitic borders commonly occur in contact with Salem Granite. *G5* granite is found to the south-east and east of this outcrop as veins and larger irregular bodies intruding the quartzo-felspathic rocks of the Etusis Formation. At the confluence of the Löwen and Leoparden Rivers (2C), as well as in the bare rock slopes extending south from here towards the Hexentanzplatz, there is extensive development of schlieric, nebulitic and diktyonitic structures on a large scale. The significant feature of this area is that in hand specimen there appears to be very little difference between *G5* and *NsGn2*,other than texture. The paleosome (*NsGn2*) is more heterogeneous and foliated, while the neosome (*G5*) is homogeneous. No chilling or contact metamorphic effects are evident and in fact many of the contacts are gradational so as to make exact definition of neosome and paleosome impossible. On Waldau a number of leucocratic, pink aplitic veins and dykes cut the Salem Granite and the orthopyroxene-bearing gabbro. A few larger red pegmatitic bodies cut the Salem Granite and are more common in the immediate vicinity of the body of Etusis Formation rocks crossing the main road (2G).

Compositionally, the specimens of this rock type examined are alkali-felspar granites (Fig.4). The rock is homogeneous and fine-grained. Microcline and orthoclase occur together with lesser plagioclase which displays albite rims in contact with alkali-felspar. Untwinned alkali felspars commonly show cloudy, altered cores and clear rims. This feature is due to exsolutions of sodium from the alkali felspars to form the albite rims on plagioclase. (Miller, 1972; appendix 1). Similar features in the previously described granitic rocks can be ascribed to the same mode of formation. Biotite is the only mafic mineral apart from occasional porphyroblastic garnet aggregates. The *G5* granite also post-dates the latest tectonic event, but the granite was nevertheless emplaced during the period of maximum temperatures in the country-rock.

8. Donkerhoek Granite (*G6*)

The major area of occurrence of this rock group is to the south-west of the map area (Faupel, 1974). As noted by previous authors (Faupel, *op.cit.*; Jacob, 1974) the most abundant phyllo-silicate is characteristically muscovite rather than biotite as in the case of other granitic members in this area.

This rock type was not examined in thin section due to it's coarse grain size. Pegmatite dykes show a pronounced banding consisting of felspars, quartz, muscovite, black tourmaline and very minor biotite. A reddish tinge to the rocks is commonly evident, while larger bodies with a similar mineralogy are not banded.

Emplacement appears to have been passive, by dilation of the schist along foliation planes. The intrusive relationship with the youngest structures (see Chapter IV) and the development of contact metamorphic features, (see Chapter V), strongly suggest that emplacement occurred after the major tectono-thermal event had reached it's peak.

E. Discussion and interpretation of stratigraphy

It is significant that many of the features described as being typical of the Etusis Formation in the Khan-Swakop area to the west, are absent in the Waldau area.

Smith (1965) and Jacob (1974) stressed the characteristic features of the Etusis Formation as being the development of conglomerates, pebble bands, massively bedded felspathic quartzite, showing cross-bedding and heavy-mineral layering. Local development of biotite-sillimanite schist occurs in the uppermost parts of the formation towards the south-east of the areas studied by them. They recognised the fact that the Khan Formation lithotypes, which are largely restricted to the north-west of the Abbabis Swell in the Khan-Swakop area, overlie the Etusis Formation, but in part display a lateral facies transition thereto.

In the Waldau area, the rocks assigned to the Etusis Formation contain no features which, on lithologic grounds, would lead one to correlate them with the Etusis Formation as described in the Khan-Swakop area, other than their quartzo-felspathic composition and the fact that they underlie the Swakop Group. Only the interlayered biotite-sillimanite schists and felspathic quartzites in the upper member in the Waldau area show any resemblance to distal lithotypes of the Etusis Formation as described from the type area. None of the sedimentary features recognised further west were found in this area. The possibility that the grade of metamorphism and migmatisation which occurred in the area, might be expected to obliterate sedimentary features, does not carry any weight when one reconsiders that relict sedimentary features are commonly evident in the extensively migmatised Etusis quartzite in the Dome Gorge area (Fig.2) (Hoffman, 1976). No possible Khan Formation lithotypes have been recognised in the Waldau area.

Jacob (*op.cit.*) described the existence of possible acid volcanic rocks from the uppermost parts of the Etusis Formation along the south-east part of his area (south-east side of the Abbabis Swell). These rocks were examined in thin section and compared with the thin sections of recrystallised acid volcanics from the Naauwpoort Formation (Miller, 1972). The obvious similarity in texture and composition between the thin sections of these rocks and those of the acid volcanics on Otjiruse, as well as those of many of the quartzo-felspathic rocks of the Etusis Formation in the Waldau area, is remarkable.

It is not possible at this stage to draw any conclusion concerning the original nature of the mass of quartzo-felspathic rocks in the Waldau area, save to stress the lack of relict sedimentary features and their similarity in texture and composition to and their association with, rocks which can be described as acid volcanics.

This sequence is correlated with the Etusis Formation in the Khan-Swakop area, on the basis of it's largely quartzo-felspathic composition and the stratigraphic position. Further studies may indicate that the greater part of these rocks have an igneous origin, in which case definition of a new formation could be warranted. It is recognised, however, that large differences in relief brought about by vertical movements might facilitate the formation of coarse clastic deposits such as a wedge arkose with a possible similarity in bulk composition to the quartzo-felspathic rocks in this area.

The iron-rich unit in this sequence can possibly be used as a marker which, from evidence in the Leoparden River, apparently transgresses from the base of the Etusis Formation on Waldau West through the gneissic units to underlie the Swakop Group on Osombanda. The lithologic associations for some type sections are shown in Table 2.

From this correlation it appears, therefore, that all units in the Etusis Formation of the Waldau area, show a distinct thinning towards the north, where the main area of Abbabis Complex occurs and must have been a palaeo-high in the pre-Etusis topography.

The rapid facies changes recognised in the Etusis and Karibib Formation, in this area , indicating deeper water conditions to the south and southwest, have led to the belief that a direct correlation can be made between the weakly cupriferous, iron-rich, sulfide-bearing, quartzo-felspathic unit, in the north and east of the area and the iron, copper and zinc sulfide-rich quartzo-felspathic unit, apparently situated in the Kuiseb Formation on Elbe and Ombujongupa Süd. The implication being that along this margin, where deeper water conditions lie relatively close by, the Nosib Group has chronostratigraphic equivalents in the lower part of the Kuiseb Formation in this area (Fig.5).

The continued deepening conditions towards the south which were apparently hinged in this region are believed to be responsible for the transgressive nature of the contact between the Etusis Formation and the Swakop Group. These features are believed to reflect early vertical movements along the Okahandja Lineament, possibly related to the initial formation of the Khomas Trough as a large graben structure.

Table 2. Lithologic associations and correlation of some type sections in the Etusis Formation

SW side of Waldau West Structure (3D)	Waldau West/ Elbe boundary (4D)	Eastern hinge of Waldau Ridge antiform (6I)	Hinge of Löwenberg antiform (6D)	East side of Otjiruse (7E)	
NsGn	NsGn	NsuS&Q NsGn	NsuS&Q	NsuS&Q	
Iron-rich sillimanite gneiss and white felsp. qzte. with pyrrh.	White felsp. qzte with pyrrh. magnetite qzte.	White felsp. qzte with pyrrh.	Iron-rich sillimanite gneiss	NsV with dissem magn. Magnetite quartzite	ETUSIS FORMATION
Ns1S? not exposed	no exposure —f—f—f—	Nodular sillimanite gneiss			
Ab	Ab	NsGn	NsGn	NsGn	
		Ns1S	not exposed	not exposed	
		Ab	Ab	Ab	

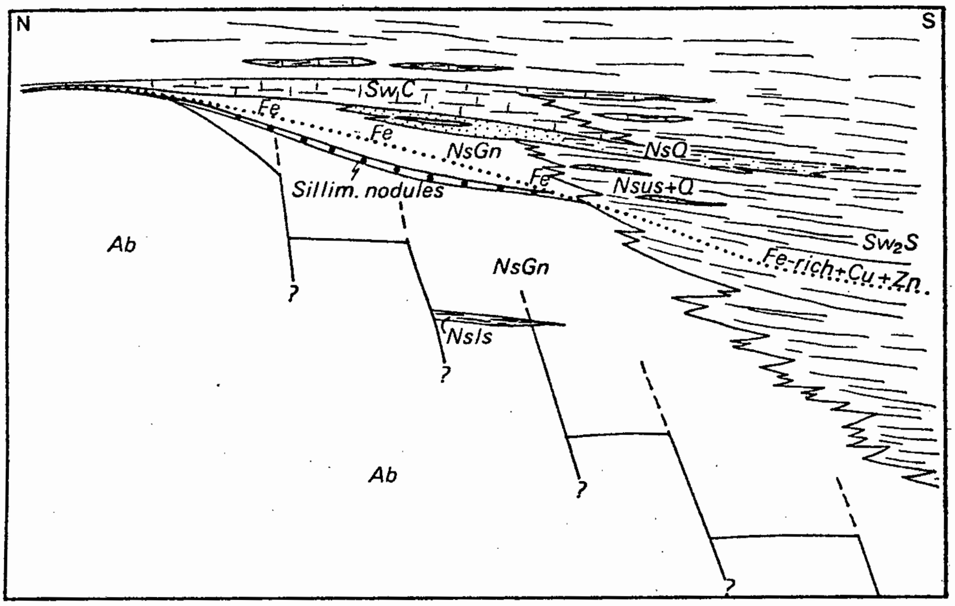


Fig.5. Schematic section showing postulated stratigraphic relationships of some lithologic units in the Waldau area. Not to scale.

IV

STRUCTURE

A. Methods and Terminology

Orientation data from mesoscopic features was collected during the course of field mapping, followed by detailed structural mapping in selected smaller areas. Some data was collected from rocks of the Abbabis Complex, underlying the Etusis Formation, but no attempt has been made to study the deformation history of these older rocks, or to relate this to the deformation history of the Damara Supergroup.

Determination of the deformation history of the Damaran rocks has been based on the generally recognised criteria outlined by Tobisch (1966): (1) deformation of the axial planes and associated lineation of earlier folds; (2) style of the folds (the terminology advocated by Fleuty (1964) has been used in this respect); (3) recrystallisation accompanying the deformation; (4) orientation of the axial planes folds. As many of these criteria as possible have been used to determine the relative sequence of events in the area.

Computer facilities were used at the University of Cape Town and in particular, routines in the Tectonic Data-Base (Hartnady and Vajner, 1975), for storage and manipulation of all structural data, as well as the plotting of stereographic projections. All data remain on file there.

All stereograms are based on the equal-area projection of the lower hemisphere of the reference sphere and are contoured by the number of data points within each 1 per cent area. The special counting net figured by Kröner (1968, p.26) which eliminates angular distortions near the edges was used in this procedure. The use of these contoured diagrams, however, is largely for descriptive and qualitative purposes only.

The size of structural elements referred to in the text are described in terms of the scale of elements which is adapted from Kröner (1968, p.23) and Whitten (1966, p.86) as follows:

Scale of elements		Outcrop size
Meso-scopic Scale	Crenulations, very small folds, some lineations	Up to approximately 10 cm wave lengths and/or amplitude
	most lineations and small folds	Up to approximately 1 m wave lengths and/or amplitude
	medium folds	Up to approximately 10 m wave lengths and/or amplitude
	big folds	Up to approximately 50 m wave lengths and/or amplitude
Macro-scopic Scale	very big folds	More than 50 m wave lengths and/or amplitude

The division of the area into Zones I and II (Fig.3) on the basis of gross structural pattern is done to facilitate ease of description with reference to the earliest recognisable planar surface in each zone. It was in Zone I that most of the structural analysis was undertaken and covers the Waldau Ridge structure, the tectonic evolution of which this study is largely concerned. Zone II covers a small part of the Okahandja Lineament and forms a subsidiary but important part of this study.

The subzones (I.A., I.B., I.C., Fig.3) outline areas in which relationships between the various deformation phases were best developed and therefore provide a basis for more detailed investigation and description. Various fabric elements will be described from the zones or subzones in which they are best developed.

Compositional banding is used in preference to bedding to describe the earliest recognisable planar surface of non-tectonic origin, due to the lack of obvious sedimentary features in these rocks other than variation in composition. This surface is annotated s_o.

The generally accepted terminology of *foliation* and *lineation* as described by Whitten (1966) is used in this study, together with the conventional annotation of s_n for planar surfaces, l_n for lineations and B_n for mesoscopic fold axes. Deformation phases in each subzone and in Zone II are annotated d_n, while the sequence of deformational events which are determined for the area as a whole are annotated D_n. Deformational phases in Zones or subzones are annotated as, for example; d_3 (I.A.) which means the third phase of deformation in subzone I.A. or d_2 (II) which means the second phase of deformation in Zone II. In all cases n = 1, 2, 3, 4.... and is relative to the earliest recognisable planar surface in each Zone.

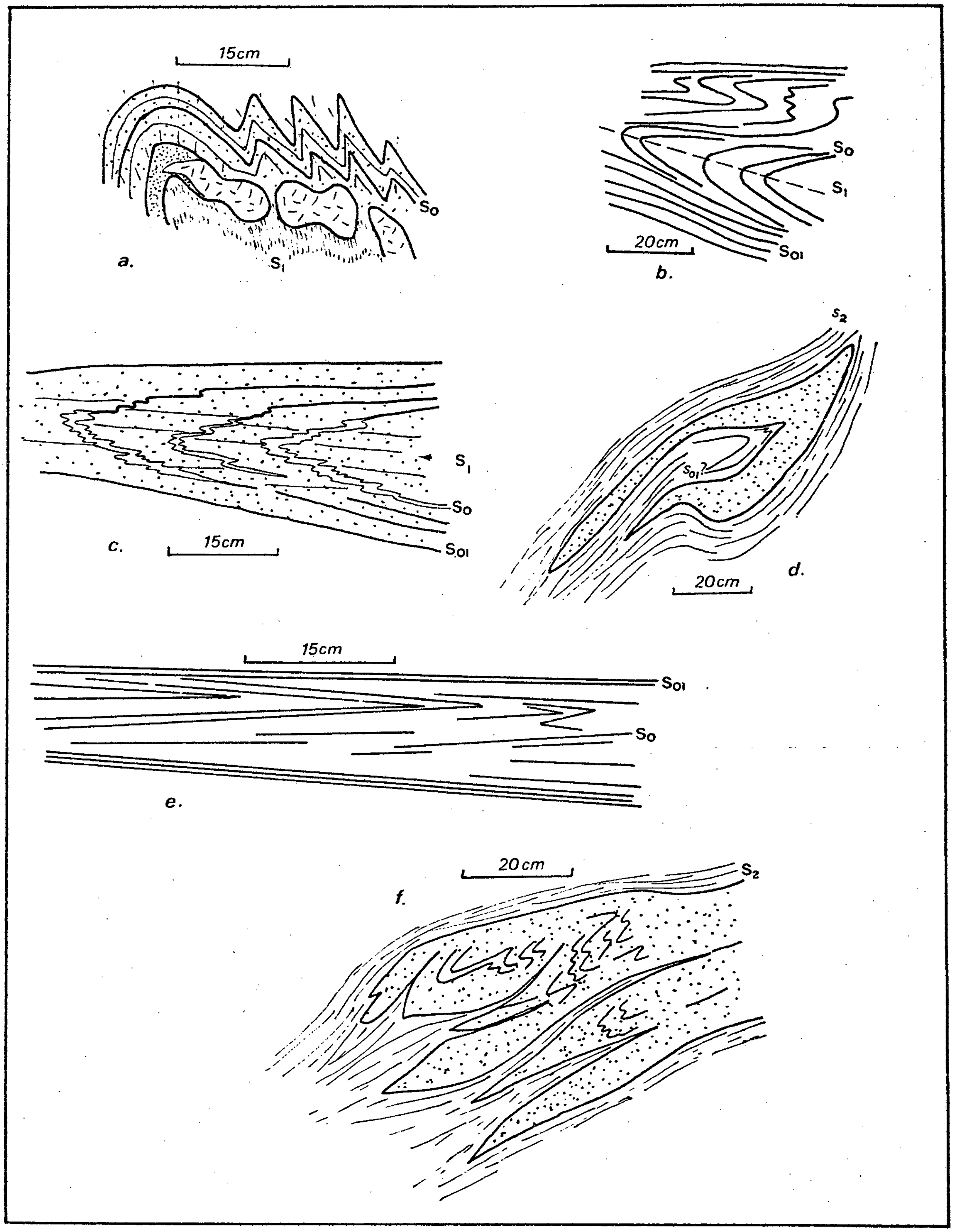
B. Structural Geometry

1. Zone I

(a) Fabric elements

(i) s_o, s_1 : The earliest recognisable planar surface in Damaran rocks in this zone are the macroscopic contacts which trace out the lithologic pattern on the geological map. On the mesoscopic scale these contacts are paralleled by a compositional layering (particularly in the calcareous rocks of the Karibib Formation) defined by varying amounts of metamorphic minerals. The distribution of these minerals is believed to reflect the primary sedimentary layering in these rocks. However it is commonly evident that some examples of this compositional banding represent the products of metamorphic differentiation, where they occassionally occur as an axial planar foliation to small folds (Fig.6c) and more commonly as planes bounding small intrafolial folds in compositional banding of similar composition. The bounding planes are seen to be parallel to the axial planes of these intrafolial folds (Fig.6b,e).

It is readily apparent, therefore, that in exposures where such meso-


15cm
So
a.
S1
20cm
So
S1
So1
b.
S2
S1
So
c.
15cm
So1
So1?
d.
20cm
15cm
So1
So
e.
20cm
S2
f.

scopic folds are not present it is not possible to conclude whether the compositional banding seen is s_0 or s_1. In fact quite commonly in such cases the planar surface measured must be described as s_{01}.

In the homogeneous, quartzo-felspathic gneisses of the Etusis Formation a weak alignment of biotite flakes is essentially parallel to the mesoscopic compositional banding and macroscopic lithologic contacts in the manner of a "stratiform foliation" (Wynne-Edwards, 1963).

Throughout much of Zone I, foliation in schistose rocks of the Kuiseb Formation and granitic and migmatitic rocks of the Salem Granite is similarly defined by alignment of biotite flakes essentially parallel to mesoscopic compositional banding and macroscopic lithologic layering.

It is therefore equally apparent that throughout much of the area of Zone I the earliest mesoscopic planar surface is best described as s_{0I}.

(ii) l_1 : In the western part of Zone I a well developed mineral lineation can occasionally be seen parallel to the hinge line of associated small intrafolial folds in calcareous rocks of the Karibib Formation. Essentially, this lineation consists of trains of fine, quartz-aggregates which are especially prominent due to the weathering out of surrounding calcareous minerals. The orientation of l_1 in this area is fairly variable due to later deformation, but nevertheless plunges either gently north or south, parallel to the trend of the macroscopic lithologic contacts.

A similar mineral lineation is commonly developed elsewhere in Zone I, but for reasons to be discussed later, caution must be exercised in interpreting all mineral lineations seen on the compositional banding as l_1.

Mineral lineations are less well developed on s_{01} planes in schistose and granitic rocks and although more prominent on quartzite bands this rock type forms a relatively minor part of the stratigraphy.

Later deformation events have also given rise to a similar mineral lineation on s_{01} planes in some areas with the result that it is often not easy to relate the distribution of mineral lineations to that which would be expected for l_1 in any particular area.

2. Subzone I.A. (Waldau Ridge antiform-east)

The area under consideration (5I, 6I, 5J, 6J on the geological map) is represented in more detail on the lithological and structural map, Folder I.

Fig.6. Typical profiles of B_1 minor folds. (See opposite page)

(a) Fabric elements

The aforegoing discussion concerning s_0, s_1 and l_1 is applicable to the area of subzone I.A. and fabric elements which can undoubtedly be seen to belong to these groups are found only in the hinge region of the Waldau Ridge antiform.

(i) *Planar elements*

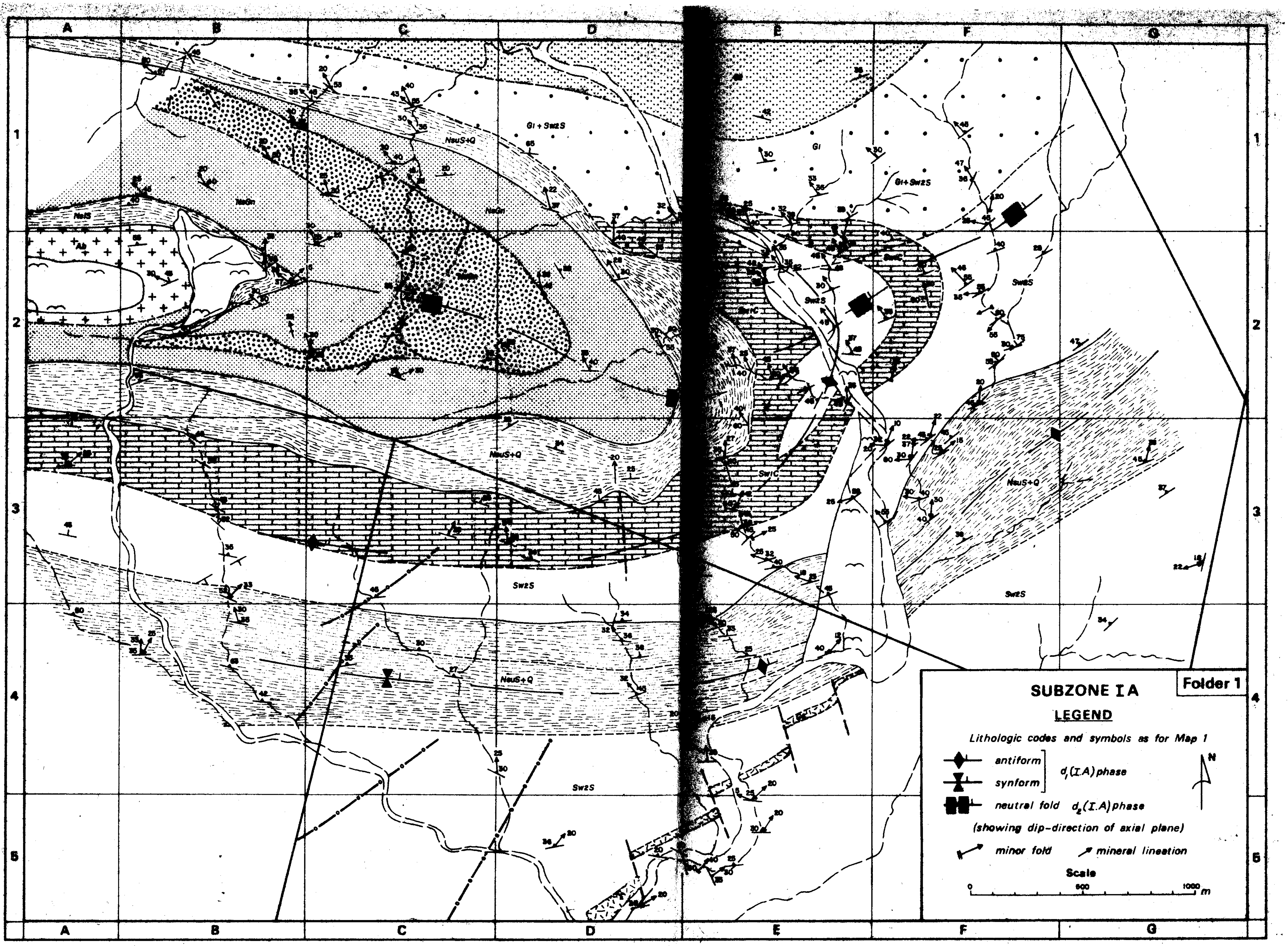
s_0 : Further to the above, there is a very restricted occurrence within semi-pelitic rocks of the Kuiseb Formation, of fine compositional banding (s_0), defined by varying amounts of biotite, which is folded isoclinally (B_1), the axial planes of these folds are in turn deformed by small isoclinal folds (B_2) whose axial planes parallel the regional schistosity.

s_1 : The axial planes of B_1 folds are defined by alignment of biotite flakes and in some layers by ovoid, fibrolite segregations orientated such that they are flattened parallel to the biotite foliation. On the limbs of the Waldau Ridge antiform, however, a similar biotite, fibrolite foliation is essentially parallel to the compositional layering and parallels the regional schistosity.

s_2 : Where mesoscopic re-folding relationships are seen, s_2 is commonly present as a non-penetrative crenulation foliation in compositionally inhomogeneous sequences, defining the axial plane foliation of B_2 folds. Biotite and fibrolite segregations, flattened parallel to the axial planes of mesoscopic B_2 isoclinal folds, make up s_2 in this hinge of the Waldau Ridge antiform (Folder I) and are parallel to the regional schistosity in this area. This foliation is thus more correctly annotated s_{12} in these areas. In the core of the Waldau Ridge antiform (Folder 1, 2B), in the lower schist member of the Etusis Formation (*Nsls*), the s_1 biotite-fibrolite foliation is strongly crenulated and refoliated to form the s_2 foliation in the hinge. Marble bands, which macroscopically, trace out the form of the Waldau Ridge antiform have, on the mesoscopic scale, been transposed to form a tectonic compositional layering parallel to s_2.

South of the Waldau Ridge in the interlayered schistose and quartzitic rocks (*NsuS+Q*), exposed in the Waldau River (Folder 1, 4E), s_2 is evident as a shallowly, north-dipping crenulation foliation in schistose rocks. Extensive transposition has occurred in thinly-layered sequences so that s_{01} has become transposed to s_2.

In the southern part of this subzone, segregation quartz veins occur commonly in the form of quartz-eyes or as rootless, fold hinges enclosed in the major biotite foliation (s_2). They occur in narrow zones up to 2 m wide and may be associated with layers showing extremely flattened, lens-like or ribbon-like granular quartz segregations enclosed by an undulating and intersecting biotite foliation (Plate I). Less commonly, zones of segregation quartz-eyes, bound narrow zones in which intense drag folding can be seen - (Plate 2). In these drag folded zones the earlier biotite foliation (s_1) is crenulated and a new biotite foliation (s_2) is formed in the axial zones of crenulations in quartz-rich bands.


Folder 1
SUBZONE I A
LEGEND
Lithologic codes and symbols as for Map 1
antiform
synform
d₁(I.A) phase
neutral fold d₂(I.A) phase
(showing dip-direction of axial plane)
minor fold
mineral lineation
Scale
0
500
1000 m
N
A
B
C
D
E
F
G
1
2
3
4
5
Gl + SwzS
Gl
NsuS+Q
NsGn
NsiS
Ab
SwlC
SwzS

In the vicinity of the hinge of the Waldau Ridge antiform the s_2 foliation which is axial planar to this fold, dips at an average of 40°N.

(ii) *Linear elements*

l_1 : A mineral lineation as described previously, is occasionally seen on compositional bands ($s_0$or s_{01}) in the Karibib Formation or on competent quartzite bands in the upper member of the Etusis Formation (*NsuS+Q*) (Fig. 7d). On the limbs of the Waldau Ridge antiform, where compositional banding and s_1 have to a large extent been transposed to s_2, it is commonly difficult to reconcile the orientation of the mineral lineation seen with that which would be l_1.

l_2 : The orientation of most mineral lineations seen in this area can be related to the orientation of the macroscopic Waldau Ridge antiform and some mesoscopic B_2 folds seen in this area.

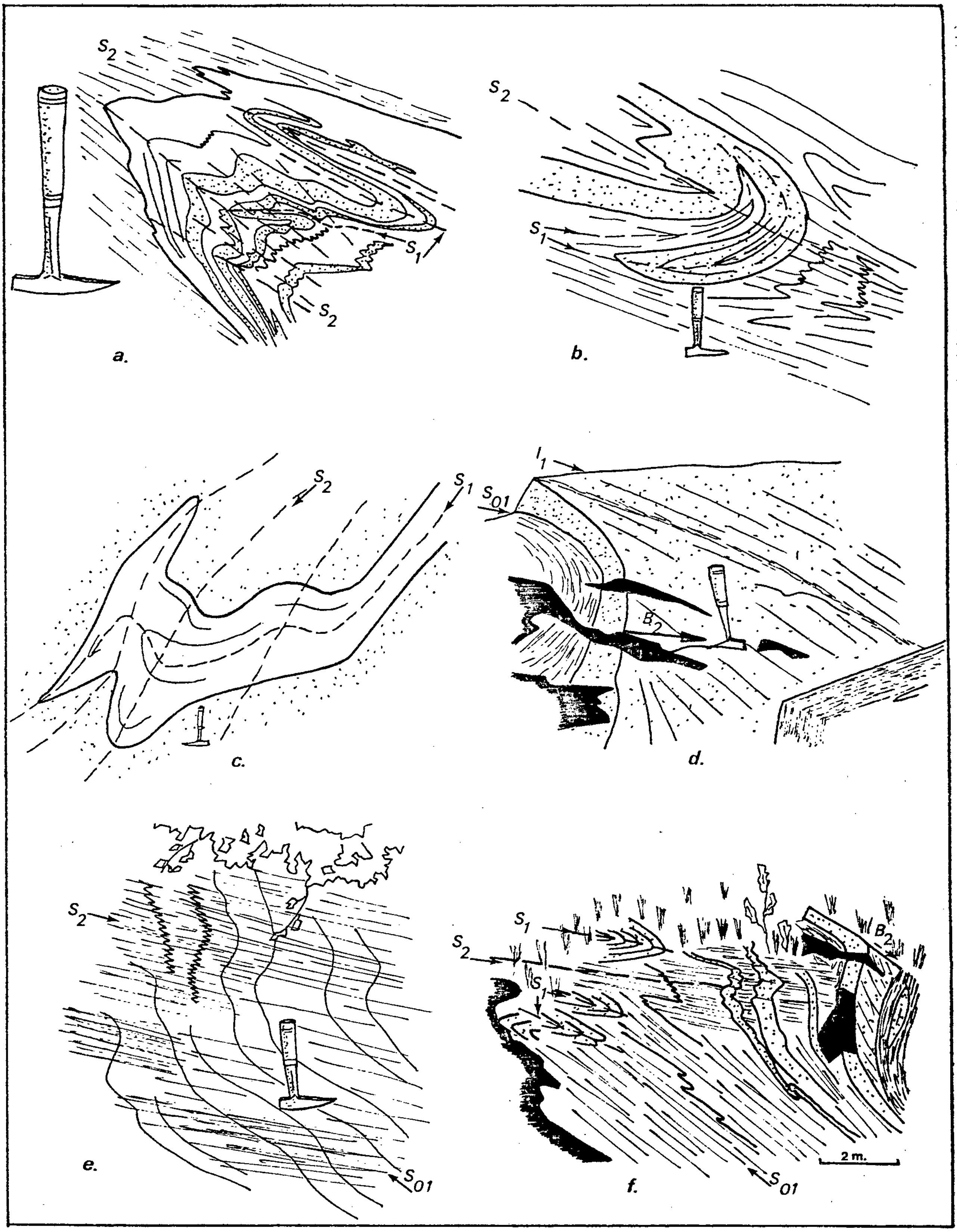
As stated earlier, in the west of Zone I a mineral lineation is occasionally seen as being parallel to the hinges of small B_1 folds. In the east, in subzone I.A. it is apparent that with the development of a penetrative transposition foliation (s_2) parallel to the axial plane of the Waldau Ridge antiform, a similar mineral lineation was produced. It thus becomes very difficult to distinguish l_1 from l_2 in this area, if l_1 in fact still exists. (See further discussion and possible solution of this problem in section IV. B.2c).

(b) Mesoscopic structures

B_1 : Mesoscopic folds which can undoubtedly be recognised as B_1 are extremely rare in this area and it was only in the hinge zone of the Waldau antiform, in the Waldau River (Folder 1, 2E) that mesoscopic refolding relationships between B_1 and B_2 were seen and therefore B_1 folds could be positively identified. The rock types in which these relationships are best preserved are semi-pelitic members of the Kuiseb Formation or interlayered schist and quartzite of the Etusis Formation, south of the Waldau Ridge.

In the few examples seen in these rocks, the B1 structures are similar folds with tight to close, rounded and less commonly angular hinges (Fig. 6a). Either single closures or "M"-type patterns (Ramsay, 1967) are observed at this locality indicating proximity to a hinge area of macroscopic B_1 folds. The orientation of the few undoubted B_1 folds in this area is shown in Fig. 9. Elsewhere in this area, mesoscopic structures, concluded to be probably B_1 folds are, in nearly all cases small, intrafolial, isoclinal, similar folds with angular hinges (Fig. 6b,c,e). These types are particularly well developed in the Karibib Formation and examples abound.

Many of these folds in calcareous rocks fall into the category of "similar folds without visible axial plane cleavage" or "flow folds" of Wynne-Edwards (1963). Wynne-Edwards has noted that all variations can exist between the end members of the series, flexural-slip (concentric), shear (similar) and flow folds. Herein possibly lies the explanation for the


S_2
S_1
S_2
a.
S_2
S_1
b.
S_2
S_1
c.
l_1
S_{01}
B_2
d.
S_2
S_{01}
e.
S_1
S_2
S_1
B_2
2 m.
S_{01}
f.

similarity between the folded compositional banding and the compositional banding of the bounding planes parallel to the axial planes of these intrafolial folds in the calcareous rocks. The banding compositional planes may represent zones of "maximum shear", bounding lobes of earlier formed folds, which was proposed by Cary (1954) as occurring in a rheid, by differential advance of adjacent fold lobes.

In the southern part of this subzone (Folder 1), "boudin-like" quartzite layers are sometimes found which display rather indistinct and irregular, intrafolial folds (Fig.6f). The orientation of these folds could not be determined, but they are assigned to B_1, as the disruption of these layers is due to transposition along s_2.

B_2 : Mesoscopic B_2 folds are not commonly seen and only in heterogeneous sequences in the hinge of the Waldau Ridge antiform and in the southern part of subzone I.A. can they be identified.

In the hinge of the Waldau Ridge antiform in the semi-pelitic sequence exposed in the Waldau River, B_2 structures are isoclinal, similar folds with rounded hinges. Immediately south of this in the upper member of the Etusis Formation (*NsuS+Q*), thicker more competent quartzite layers have been folded concentrically (Fig.7d,f) but nevertheless may form close, tight or isoclinal folds with rounded hinges. In more thinly interlayered quartzite and schist sequences, small, isoclinal, similar B_2 folds occur.

There is, in detail, very little difference between the form of mesoscopic B_1 and B_2 folds and it is often only possible to distinguish them unambiguously in the localities described above, when refolding re*lationships* are seen (Fig.7b,c).

B_3 : North-east trending (Fig.17), upright, concentric mesoscopic folds occur most noticeably in the heterogeneous sequences in this area. These folds show varying degrees of tightness from gentle warps, through open and close, to tight structures all with rounded hinges. An axial plane foliation to these folds is not developed in heterogeneous sequences. A north-east trending crenulation lineation is weakly developed on some outcrops of schistose rocks in more homogeneous sequences.

(c) Macroscopic structures

The lithologic pattern represented on Folder 1 and generalised in Fig.8 shows the macroscopic relationships between B_1 and B_2 in subzone I.A. It is by reference to this macroscopic pattern and distribution of lithologies that

Fig.7. Examples of refolding relationships of B_1 by B_2 in subzone I.A. (See opposite page)

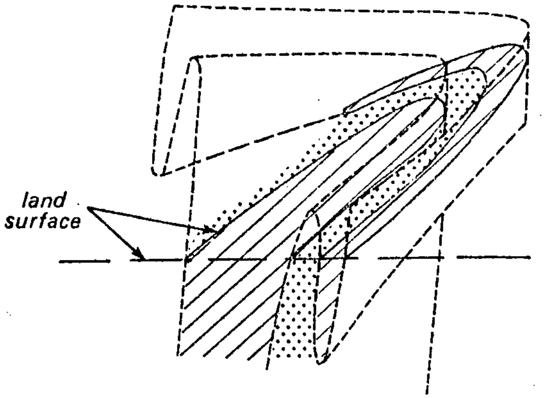
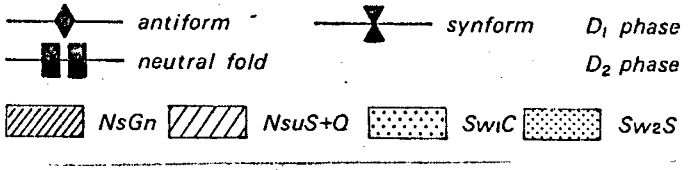


Fig.8b. 3-dimensional sketch of B_1/B_2 relationship in fig. 8a.



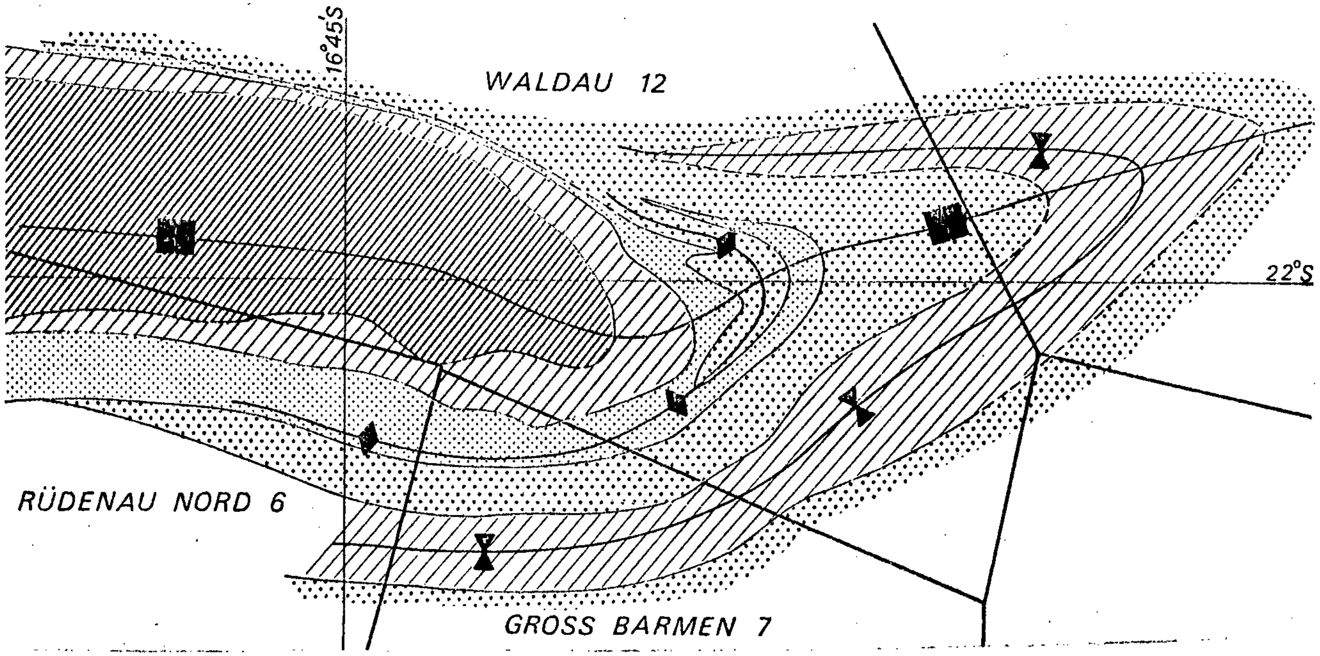
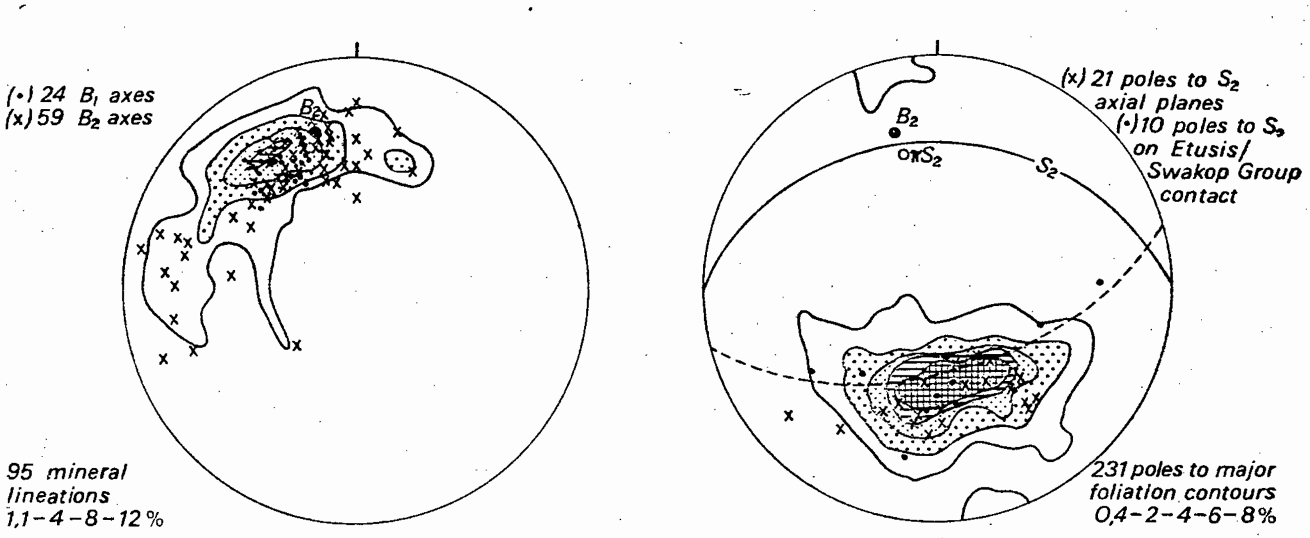


Fig. 8a Generalised lithological distribution and interpreted macroscopic B_1/B_2 relationships (Subzone I.A.).

the mineral lineation problem in this area and whether the distribution of mineral lineation on the stereogram (Fig.9) is related to B_1 or B_2, can be resolved.

Subzone I.A. was subdivided into 5 domains (*sensu* Turner & Weiss, 1963 p.20) (1 to 5 inclusive) (Fig.10) each of which was considered to be homogeneous with respect to the major foliation, in order to reduce the distortion due to later events (Fig.9). The prominent mineral lineation was plotted for each



Linear elements **Planar elements**

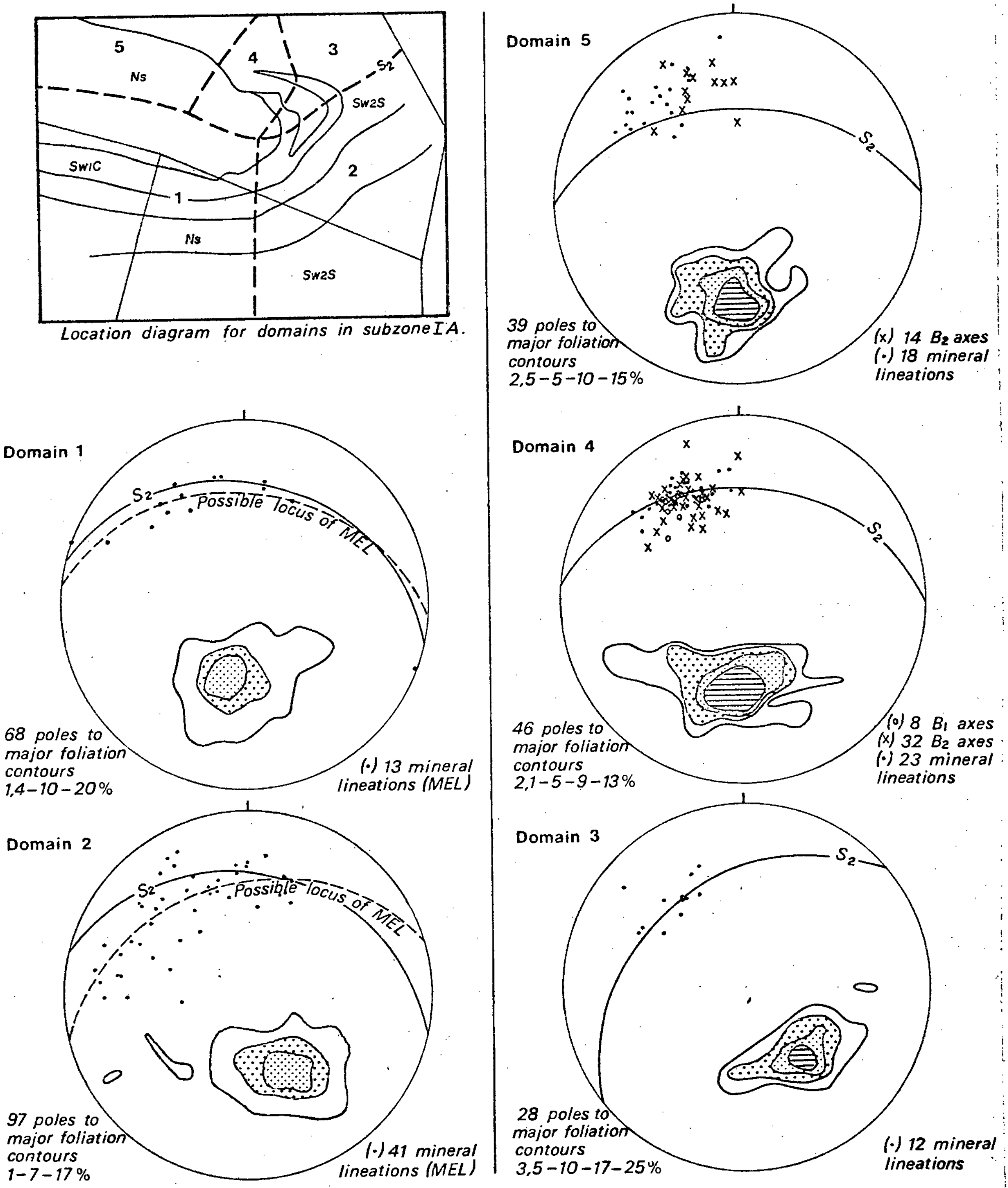
Fig.9. Synoptic diagrams for subzone I A.

domain and its relationship to the major foliation on which they were measured, was examined. Assuming that the mineral lineation seen is in fact l_1, then its relationship to s_2 could help define the orientation of the kinematic axes related to B_2 in this area (Ramsay, 1960).

Domains 1 and 2 (Fig.10) on the south side of the Waldau Ridge antiform, show pronounced homogeneity with respect to foliation and in both domains a possible great circle locus can be fitted to the spread of mineral lineations. Data from domain 1 is rather sparse and the fit is not very good, which may indicate a component of concentric folding or, that there may have been tightening up of folds during later deformation (post-B_2), causing the lineations to rotate off the great circle locus (Ramsay, 1960).

Domains 3, 4 and 5 on the north side of the axial-plane to the Waldau Ridge antiform (Fig.10), display relative homogeneity with respect to foliation and in contrast to domains 1 and 2, considerably less spread of mineral lineations, thus making it practically impossible to apply a reasonably good fit of great circle locus to these data.

Comparison shows that a similar relationship between foliation and concen-



Location diagram for domains in subzone IA.

Fig.10. Structural data for domains in subzone IA.

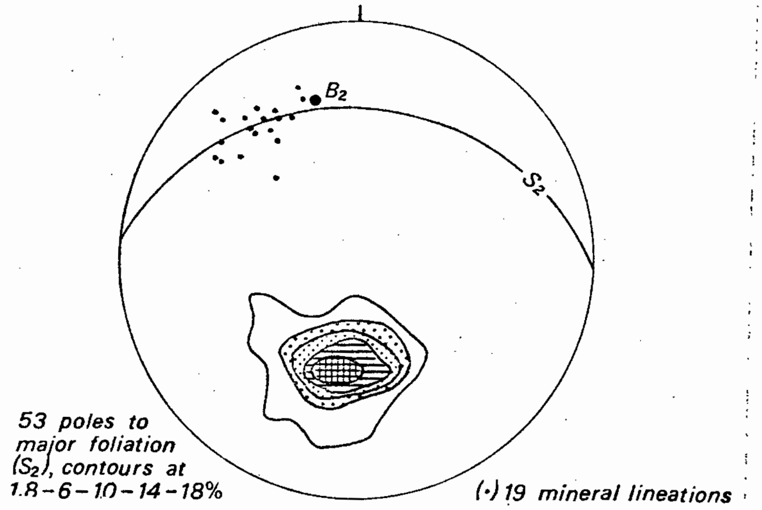


Fig.11. Structural data from NsGn in closure of Waldau Ridge antiform

tration of mineral lineation exists among the data in Fig.11 and also that for domains 3, 4 and 5 in Fig.10. This can be interpreted as indicating that l_2 is the dominant mineral lineation represented to the north of the axial plane of the macroscopic B_2 fold. Conversely then, it might be possible to conclude that the mineral lineations to the south of the axial-plane in this area are to a certain extent more representative of l_1.

This problem of the apparently better development of l_2, north of the axial-plane of the Waldau Ridge antiform, can possibly be resolved by reference to the distribution of lithology in this vicinity (Fig.8). The pattern in the unmapped area to the east of Waldau and the area now occupied by G1 and G2 granite to the north, is interpreted on the basis of mesoscopic re-folding relationships and some reconnaissance mapping. It can be seen from Fig.8a that the major expression of macroscopic B_1 folds occurs on the south side of the B_2 axial-plane, and that the facies change from carbonate-rich Karibib Formation, to more pelitic Kuiseb Formation on the north side, means that s_2 is developed as a more penetrative foliation in these more suitable lithotypes, than to the south where the greater abundance of more competent lithogies south of the Waldau Ridge have resisted the complete transposition of s_1 and the obliteration of l_1 lineations.

The only mesoscopic folds seen which show a re-folding relationship between B_2 and l_1, occur in interlayered schist and quartzite in the south of the area (Folder 1, 4E). Slip folding and the development of an axial planar crenulation foliation (s_2) has occurred in the schistose and very thinly layered rocks, while thicker interlayered quartzites are deformed by flexural-slip and no s_2 axial plane foliation is developed. It is on these thicker more competent layers that the l_1 lineation is preserved (Fig.7d). Exposures were unfortunately, not sufficiently good to enable enough measurements to be taken in order to make a stereographic representation of the relationship meaningful. Further, the layers on which l_1 is preserved, show concentric forms, which means that the relationship could not be used to define kinematic axes with respect to B_2 (Ramsay, 1960).

It is concluded that no useful information could be gained from lineation deformation patterns concerning the orientation of the kinematic axes with respect to the macroscopic B_2 fold in subzone I.A. In domains 1 and 2 it is likely that the population of mineral lineations is not homogeneous with respect to origin, i.e. it is not possible to distinguish mesoscopically, the difference between l_1 and l_2 which results in the poor fit of great circle locii. In domains 3, 4 and 5 complete transposition of s_1 and with it obliteration of l_1 has occurred with the result that only l_2 is represented.

B_1 : The orientation of the few undoubted B_1 folds in the hinge of the Waldau Ridge antiform (Fig.9) are from one locality only and therefore cannot be considered representative of all the possible orientations of B_1 after deformation by B_2. No firm conclusions can be drawn regarding the original orientation of B_1 folds from this area except that they probably formed an angle near 90° with the trend of B_2 folds, but their axial planes were transposed to become parallel to the limbs of the Waldau Ridge antiform (B_2).

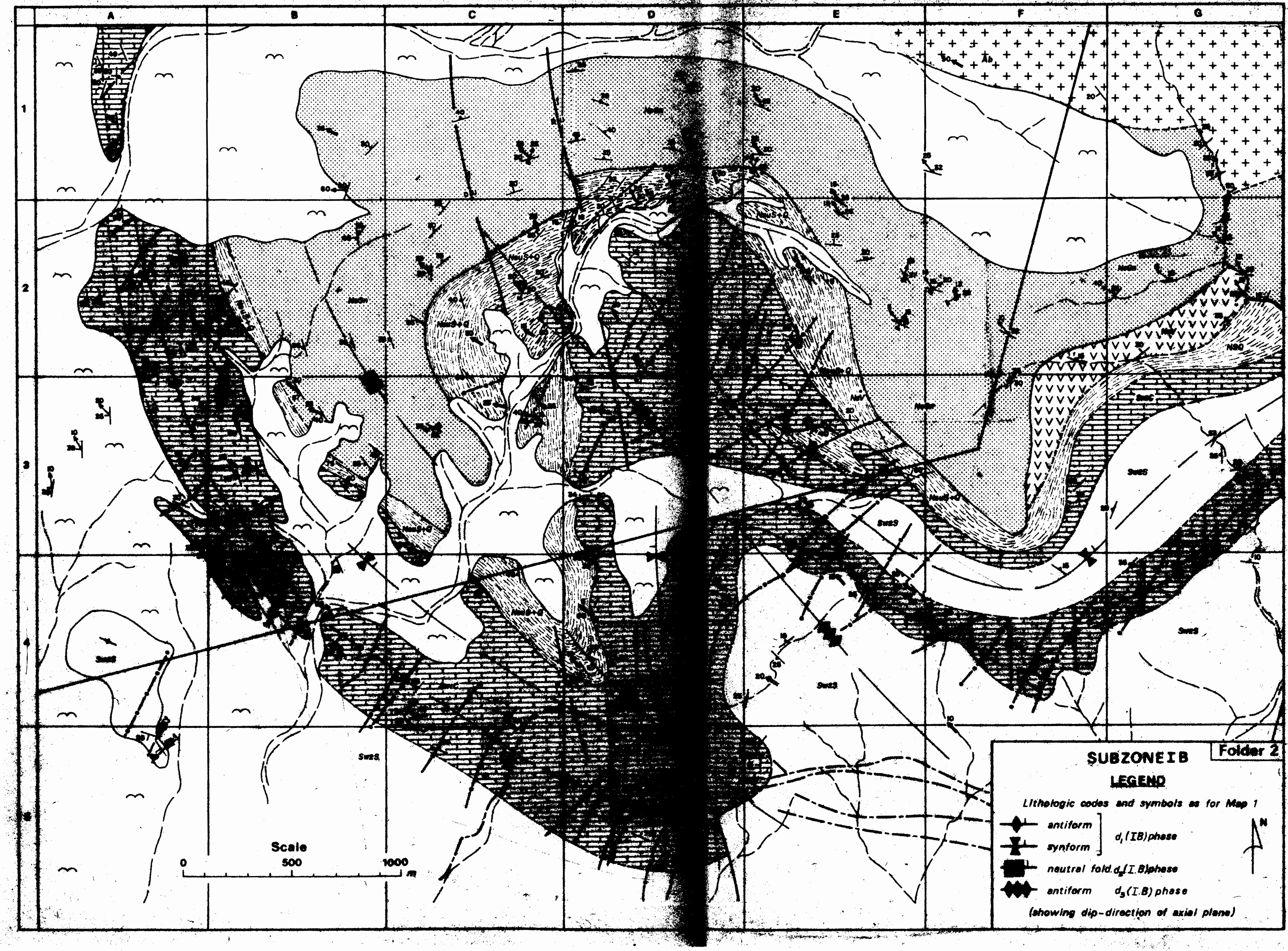
B_2 : The Waldau Ridge antiform is the macroscopic representative of B_2 in subzone I.A. This structure is isoclinal with a rounded hinge and its axis plunges down the dip of its axial plane in the manner of a reclined or neutral fold. This fold is further characterised by a macroscopically penetrative axial planar foliation and a regional schistosity in schistose rocks, which parallels the limbs of the fold.

B_3 : No readily apparent macroscopic B_3 folds can be seen in subzone I.A., except that the curvature of the macroscopic B_2 axial plane at the hinge of the Waldau Ridge antiform is believed to reflect the proximity of a macroscopic B_3 antiform whose axial trace coincides with the north-east trending dyke of *G6* granite (71) and which passes through the south-east corner of subzone I.A. The presence of this fold has been confirmed by reconnaissance mapping to the east of Waldau. Curvature of s_2 shows a fold axis which plunges parallel to the hinge of the Waldau Ridge antiform (Fig.9) rather than to the north-east, as shown by mesoscopic B_3 fold axes (Fig.17) in this vicinity.

3. Subzone I.B. (Löwenberg antiform and Waldau Ridge antiform-west)

Folder 2, shows in more detail the lithologies and structural relationships in this subzone (Fig.3).

The thinly layered rocks of the Karibib Formation (*Sw1C*) and the upper member of the Etusis Formation (*NsuS+Q*) once again provide the most information on fabric elements related to at least three phases of deformation. Exposures are fair to good except in the hinge area of the Waldau Ridge antiform-west (Folder 2; 4C, 4D) where they are poor.


A
B
C
D
E
F
G
1
2
3
4
5
Folder 2
SUBZONE I B
LEGEND
Lithologic codes and symbols as for Map 1
antiform
synform
d_1(IB)phase
neutral fold d_2(I.B)phase
antiform d_3(I.B) phase
(showing dip-direction of axial plane)
N
Scale
0
500
1000
m
Sw2S
NSO
Ab

(a) Fabric elements

(i) *Planar elements*

s_0 : Other than the macroscopic lithologic layering, s_0 is seen only occassionally as intrafolially, folded bands in the Karibib Formation similar to those described previously.

s_1 : A biotite and biotite-fibrolite foliation essentially parallel to the compositional layering in the Etusis and Kuiseb Formations, is recognised as s_1 and is the dominant schistosity in this vicinity. In the Karibib Formation s_1 was once again recognised as being represented by the compositional banding which bounds intrafolial folds of s_0 and which is parallel to the axial planes of these folds (Fig. 6e). More correctly therefore, s_{01} is the most common planar element seen in subzone I.B.

s_2 : This western hinge of the Waldau Ridge antiform is markedly different to its eastern counterpart, in that no mesoscopically penetrative axial plane foliation is developed in this area. It is possible that such features exist in the poorly exposed hinge area but are probably not extensively developed as competent lithologies are more common in this area than in the hinge area of this fold in subzone I.A.

s_3 : A mesoscopic planar fabric related to the Löwenberg antiform is not developed.

s_4 : This weakly developed, mesoscopically non-penetrative planar element is most commonly seen in the homogeneous quartzo-felspathic gneissic rocks of the Etusis Formation as small shear zones which parallel the axial planes of small, assymmetric, similar folds (Plate 3). These shear zones commonly occur in the steeper limb of these folds causing attenuation thereof and the enhancement of the small antiforms between bounding shear zones. Slightly pegmatitic unfoliated neosomes commonly occur in these shear zones. It is rarely possible to obtain more than a trend from the orientation of this element in these homogeneous rocks.

(ii) *Linear elements*

l_1 : Due to the fact that a penetrative s_2 foliation is not developed in this area the mineral lineation occassionally seen on s_0 and s_{01} is concluded to be l_1, particularly as it commonly parallels the hinge of small intrafolial folds (B_1). The orientation of l_1 is rather variable due to the effects of three post-B_1 phases of deformation in this area and no attempt was made to study the relationship of l_1 to later phases of deformation in this area, due to the paucity of suitable exposures.

(b) Mesocopic structures

Little can be added from this area concerning the form of mesoscopic B_1 folds which are similar to those described previously from subzone I.A. No mesoscopic B_2 folds were recognised in this area.

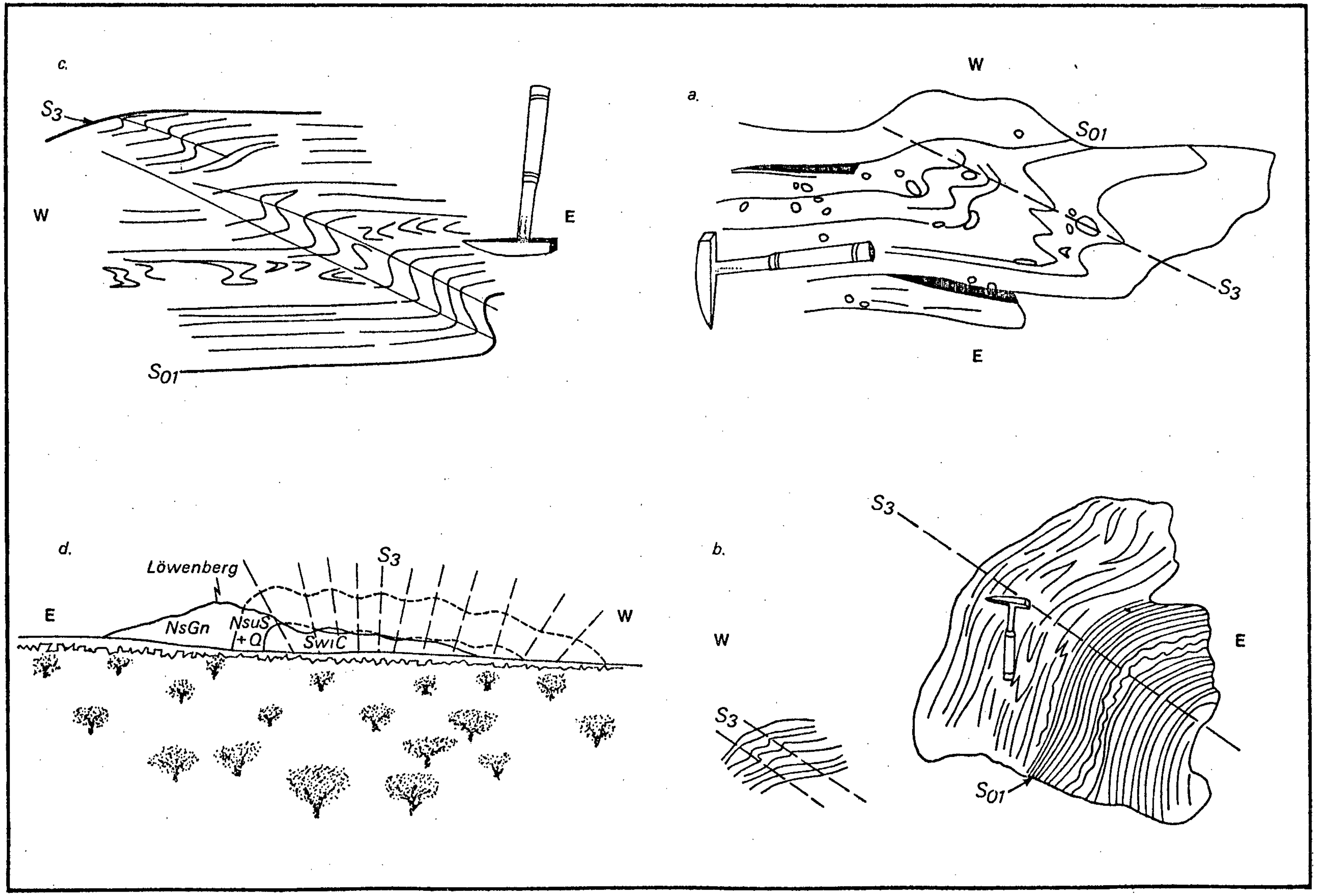


Fig.12. B_3 folds from subzone I.B.

B_3 : Mesoscopic B_3 folds show consistent open concentric forms but which, in the core of the Löwenberg antiform (Folder 2; 3E) are considerably tighter (Fig.12a) than in the envelope (Fig. 12b), where close folds are only occassionally seen in the thinly banded calcareous rocks (Fig.12b). Folds may also be irregular, particularly in sequences containing interlayered marble bands. Occassionally chevron folds develop to form "kink bands" (Fig.12c) and less commonly chevron folds occur with axial planes dipping in a direction which is conjugate to that shown by the other folds in the vicinity. Crumpling of the calc-granofels bands may sometimes occur and can possibly be related to local deformation by drag, through flexural-slip on enclosing surfaces.

Plunges of mesoscopic folds vary from 5° to 20° in the south-east, on the limbs of the macroscopic B_1 folds to approximately 35° in the north-west on the southern limb of the macroscopic B_2 fold (Waldau Ridge antiform) as defined by the contact between the Etusis Formation and the Swakop Group. The spread of B_3 axes (Fig.13c) possibly relates to the effects of later deformation on the distinct fan-shaped orientation pattern of axial planes to the mesoscopic folds which diverge from the hinge zone of the Löwenberg antiform (Fig.12d)

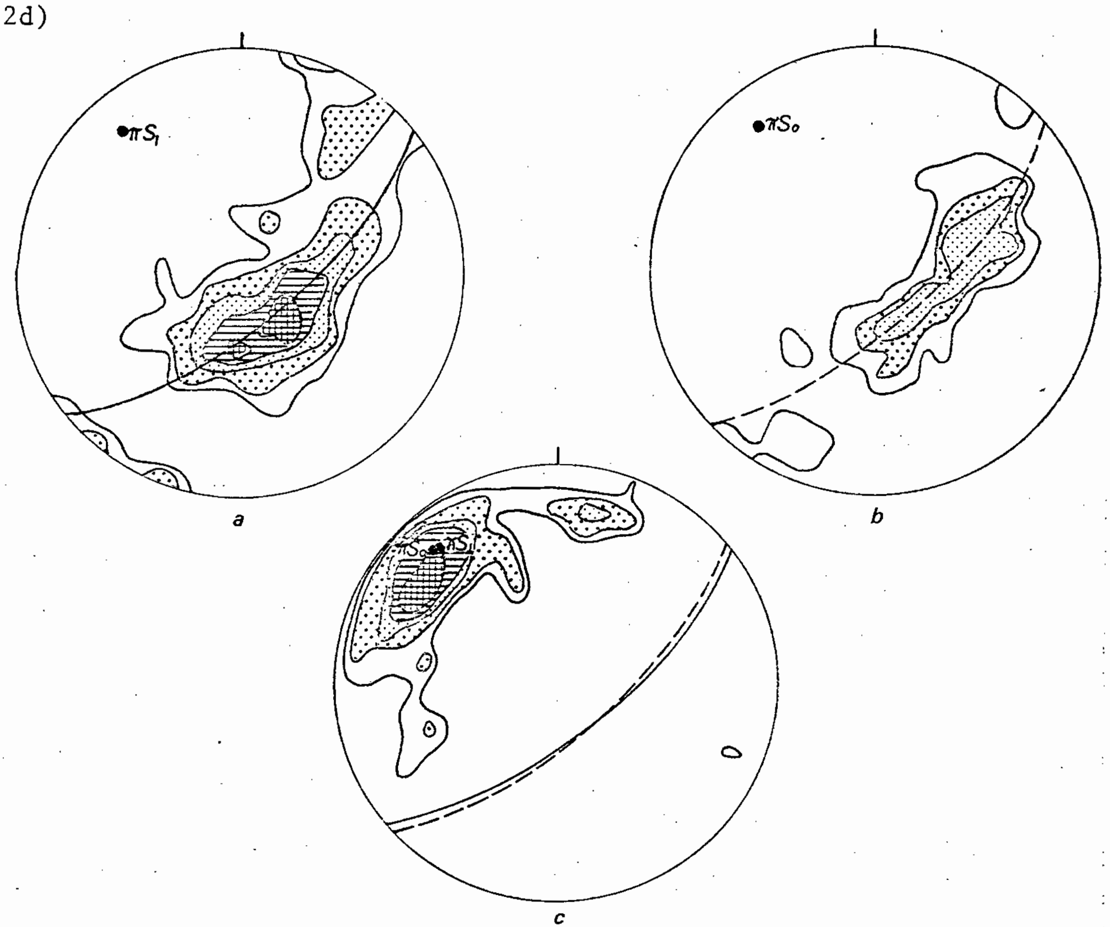


Fig.13 . Structural data from subzoneIB(Löwenberg antiform).

a) 129 poles to major foliation (S_1), contours 0,7-2-4-6-8%
b) 163 poles to composition planes (S_0), contours 0,6-1,5-3-4,5%
c) 85 B_3 fold axes contours 1,2-2-4-6-8%

B_4 : As noted previously, small north-east or south-west trending (Fig. 17) similar folds occur mainly in the quartzo-felspathic gneisses of the Etusis Formation (Plate 3). They are characteristically assymetric with the steeper limbs attenuated by minor shear zones (s_4). Antiforms are characteristically more enhanced than synforms in adjacent structures.

(c) Macroscopic structures

B_1 : The trends of l_1 and the orientation of s_{01} in the western part of subzone I.B. and in the zone of Karibib Formation rocks which trend north from here along the west side of the Waldau Ridge structure indicate that the macroscopic B_1 folds of the area have nearly horizontal axes and axial planes which dip at moderate angles to the west. The axial planes steepen in the south of the area and become overturned towards the south with gently northwards dips, where they are folded around the hinges of the Waldau Ridge antiform-west and the Löwenberg antiform.

B_2 : The axial orientation of the Waldau Ridge antiform in this area is not clear and cannot be determined exactly due to the lack of mesoscopic B_2 folds and the effects of later deformation. From the macroscopic relationships it is believed to be a reclined isoclinal hinge which plunges in a westerly direction.

B_3 : The orientation of the Löwenberg antiform in subzone I.B. is well defined by the data from mesoscopic features as shown in Fig.13 and field relationships confirm that it is a gently north-west plunging, upright, asymmetric open fold which has a rounded hinge and steeper limb to the east (Fig.12d).

B_4 : Although there is no obvious macroscopic feature in this area which can be recognised as a B_4 fold, the slight curvature of the axial trace of the Löwenberg antiform in this area indicates that it has been deformed by a major B_4 fold which trends in a north-easterly direction from 4B to IE (Folder 2).

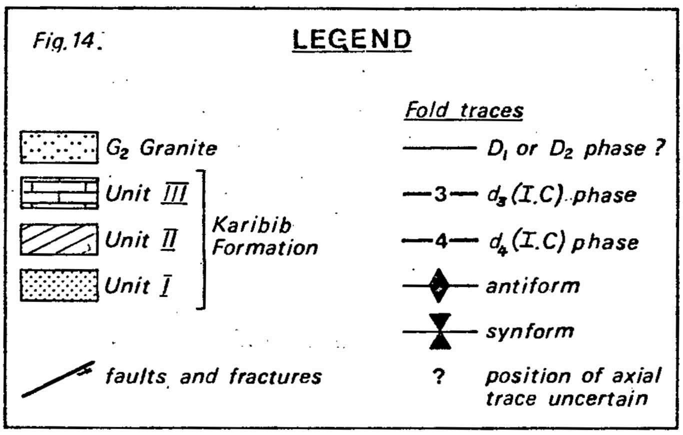


Fig. 14.

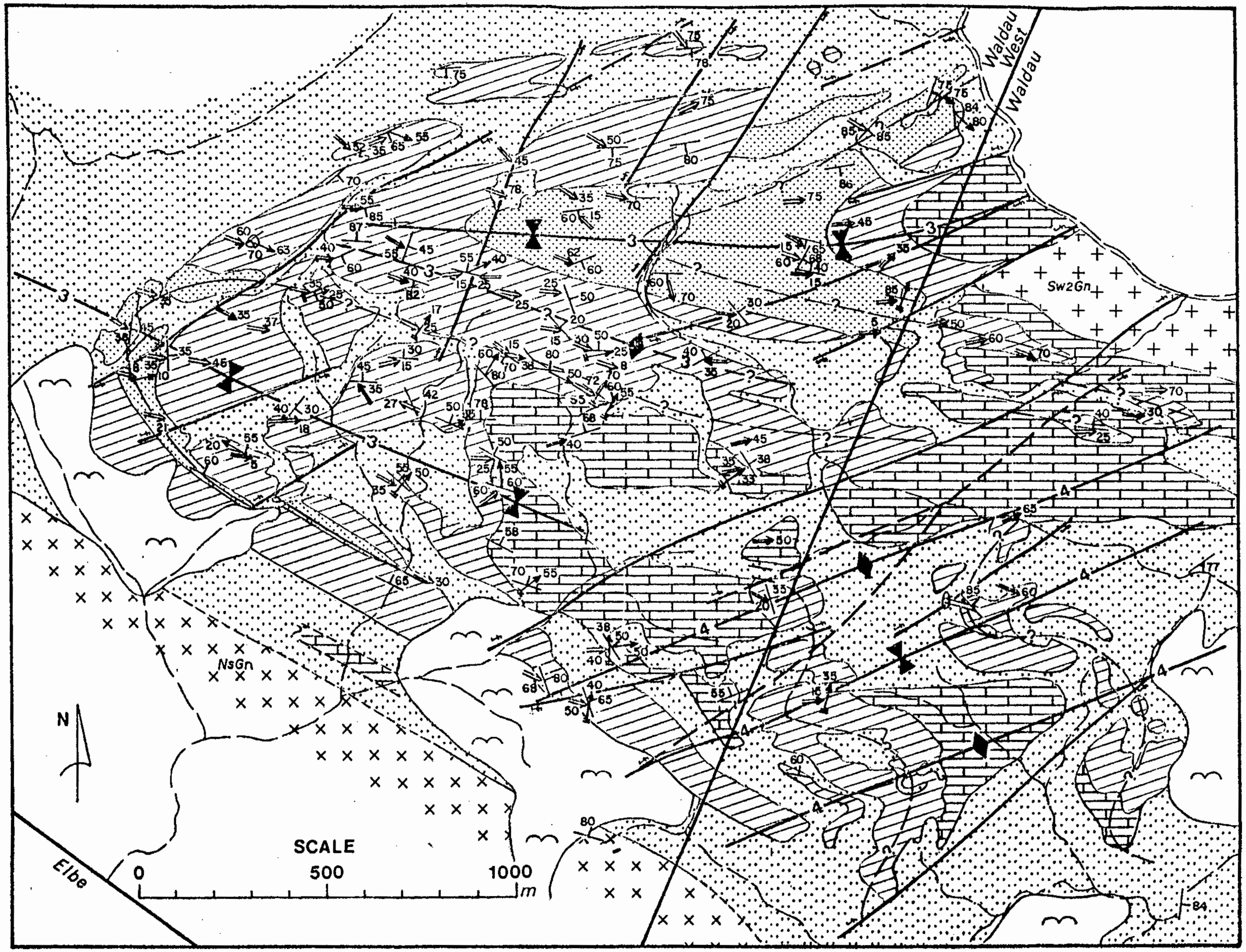


Fig.14. Subzone I.C.(Legend see opposite page)

(d) Faults

Faults are fairly common in this area and can be related in trend to s_4 foliation planes and are especially noticeable due to the fact that many of these fault planes are the locus of intrusion of dykes of *G3* granite. Similar features are evident in the north trending zone of Karibib Formation rocks to the north of this area. Displacement along these faults is only evident in the horizontal plane and a left-lateral movement is shown by all examples seen. None of these faults are seen to penetrate the Etusis Formation where the movement appears to have been taken up in numerous minor shear zones with similar trend and apparent displacement (s_4).

4. Subzone I.C. (Ritter synform)

More detailed relationships in the area of 4E and 4F on the geological map are shown in Fig.14, which comprises subzone I.C. (Fig.3). The investigation in this area dealt almost entirely with rocks of the Karibib Formation and in order to assist the unravelling of the structural relationships the Karibib Formation was broadlv subdivided into three units on lithogic criteria, in stratigraphic order from uppermost to lowermost:

Unit III	Interlayered calc-granofels and marble;
Unit II	Light coloured calc-quartzite with interlayered calc-granofels;
Init I	Quartz-amphibole gneiss and dark coloured calc-quartzite.

The *G2* granite is relatively homogeneous and not well exposed in this area, therefore little fabric orientation data was obtained from it. The units I and II above are well exposed, however much care must be exercised as many outcrops consist of slumped blocks. Unit III is less well exposed and does not form such prominent topographic features as do units I and II.

(a) Fabric elements

(i) *Planar elements*

Compositional banding, s_{01}, is the best developed planar element in this subzone and previous descriptions of the nature of this element from other subzones are also pertinent to this subzone.

s_3 : Although an axial plane foliation is not mesoscopically developed in the rocks of the Karibib Formation, a weak foliation defined by sub-parallel orientation of biotite flakes is commonly seen in the *G2* granite. While the orientation of this foliation is not readily measureable it can be correlated in trend with the axial plane of the macroscopic B_3 fold in the area (Ritter synform).

(ii) *Linear elements*

A mineral lineation similar to l_1 in other areas is occassionally seen on s_{01} planes, however too few were encountered in any particular portion of the subzone to make further study of the relationship to later deformation phases meaningful.

(b) Mesoscopic structures

The form of the few B_1 intrafolial folds seen in the area are similar to those described from other areas and is therefore not repeated here.

B_3 : Mesoscopic B_3 folds have largely concentric form while thinly banded sequences commonly show development of small chevron folds (Fig.15a) and sequences in which marble bands are more common, some folds show gradation to similar forms (Fig. 15b).

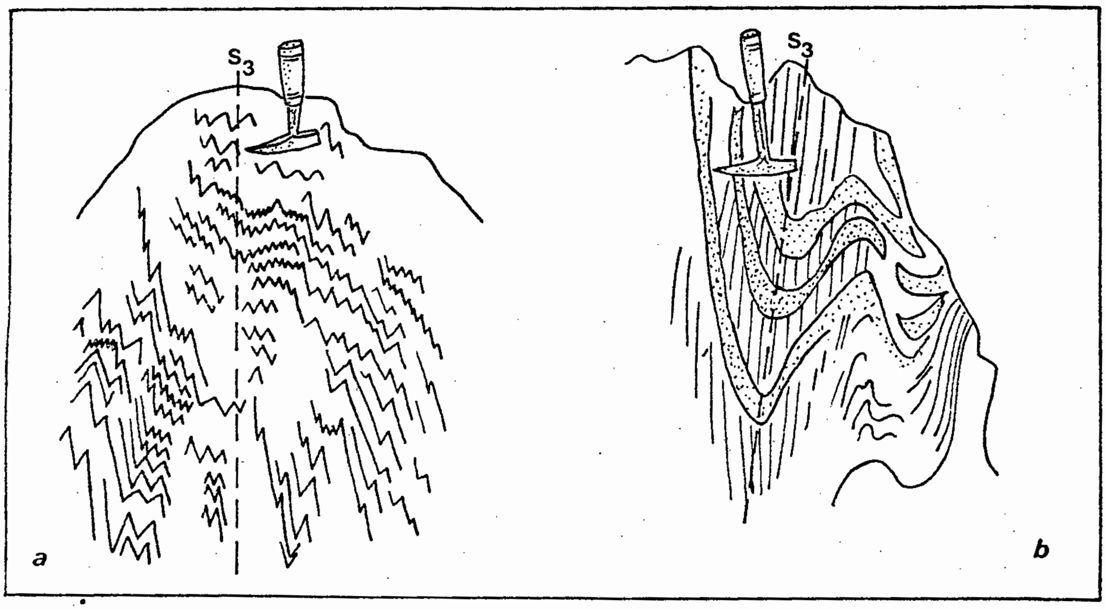
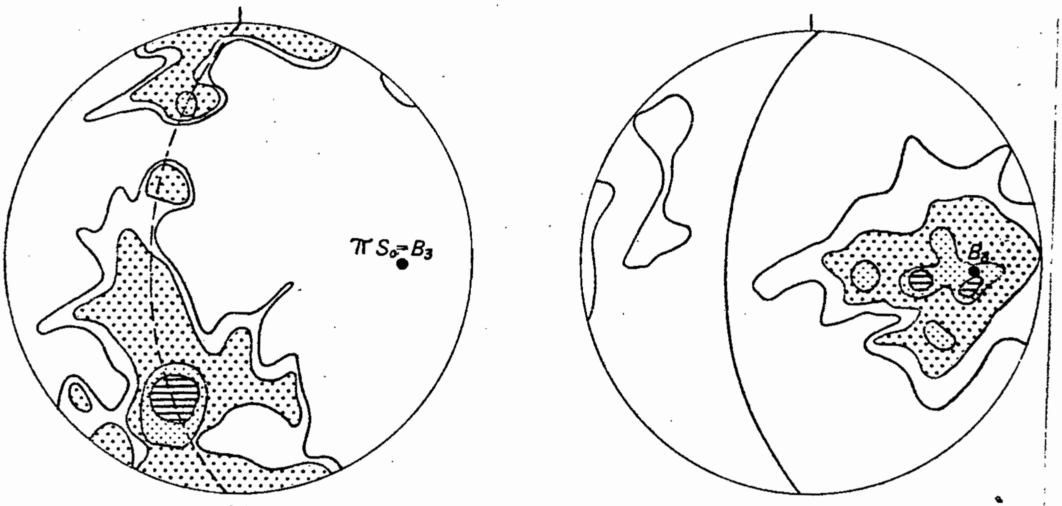


Fig. 15. B_3 folds from subzone I.C.

The plunge of mesoscopic folds in these calcareous rocks define a spread of three small maxima, plunging at 70°, 45° and 30° in a direction of 095°, approximately along the axial plane of the macroscopic fold system and a single maxima with a plunge of 45° in a direction of 120° (Fig.16b).

Occasionally in schistose rocks a short distance to the east of subzone I.C. an east trending crenulation lineation can be correlated with the major trend of these B_3 folds.

B_4 : North-east trending mesoscopic B_4 folds (Fig.17) are occasionally developed in the western part of subzone I.C. The concentric style of these folds is similar to that of some B_3 folds in this area, except that they trend



(a) (b)

Fig. 16. Structural data from subzone I.C. (Ritter synform)
a) 82 poles to composition planes (S_0), contours 1,2–2–4–6%
b) 111 B_3 fold axes, contours 1–3–5–7%

some 20°–80° north of the B_3 maxima. Re-folding relationships between B_3 and B_4 were not seen on this scale. In the east, where B_4 folds become larger, relationships with B_3 were similarly not seen due to granite intrusions and poor exposures.

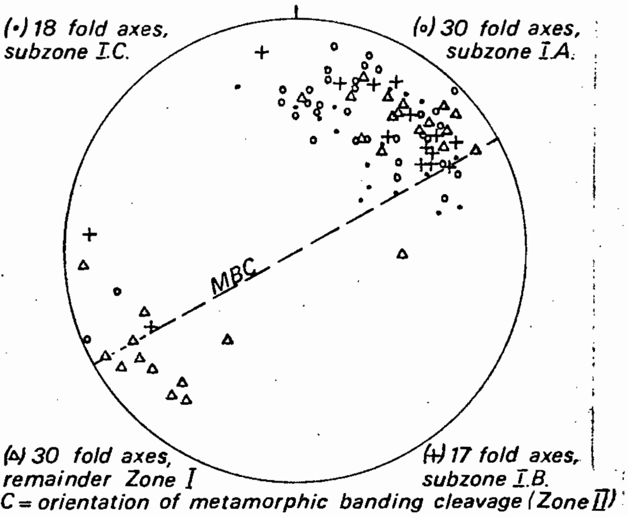


Fig. 17. Structural data for Zone I, D_5 phase

(c) Macroscopic structures

Pre-B_3 : Macroscopic folds which predate B_3 can be identified through the three fold subdivision of the Karibib Formation in this area, as having cores of darker coloured, Unit I rocks, which are readily identifiable on aerial photographs. These curvi-linear, dark coloured zones which are the hinge zones of pre-B_3 folds outline the form of B_3 folds in the west and B_4 folds in the east of subzone I.C. (Fig.14).

B_3 : The orientation of the Ritter synform in this area can be clearly seen from the detailed geological map (Fig.14) and is confirmed by the mesoscopic orientation data (Fig.16), from which it appears that the macroscopic axial plane of the Ritter synform is near vertical and trends approximately due east. In the centre of the area a tight antiform separates the two, more open synforms of the macroscopic structure, in repetition of a commonly observed mesoscopic feature.

The disorientation of B_3 axial planes by B_4 in the east of subzone I.C. (Fig.14) is not apparent in the stereograms (Fig.16) because relatively little data was collected in the east due to poor exposure and granite intrusion. The irregular spread of composition planes (Fig.16a) and the spread of orientation of mesoscopic B3 axes can, in part, be attributed to local disorientation by B_4 (eg. reversed plunges of B_3 to the west).

B_4 : These folds are macroscopically evident in the eastern part of subzone I.C. (Fig.14), where their form is most clearly defined by the folded hinge zones of pre-B_3 folds. The axial plane trace of the northernmost B_3 synform is clearly disorientated by the north-east trending B_4 folds. (Fig. 17).

(d) Faults

North-east trending faults with consistent left-lateral displacement are clearly evident in the central and western part of the subzone I.C. (Fig.14). Their orientation can be related to that of the macroscopic B_4 axial planes and they commonly have acted as the locus for intrusion of dykes of *G3* granite.

5. Subzone I.D. (Waldau River section-north)

The Waldau River (7I-12I) provides a convenient section line, with good exposures in the river banks, joining the Waldau area proper and Gross Barmen hot springs, which is the northern limit of the area covered by Hälbich (1970) in his structural synthesis of the Khomas Synclinorium. The lithology encountered is entirely that of the Kuiseb Formation, which unfortunately, due to its largely homogeneous composition, is not ideal for the purposes of structural analysis. However, in this northern section (7I-9I) (Fig.3), some compositional variation does occur, with bands of quartzite, calc-granofels, marble and quartz-amphibole schist being interlayered with the homogeneous quartz-biotite schist.

(a) Fabric elements

(i) *Planar elements*

A tectonically developed compositional layering is the most commonly seen planar element in this area. A primary compositional layering (s_0) not parallel to either s_1 or s_2, is not readily identifiable at any locality in the section.

s_1 : An earlier biotite foliation pre-dating the regional schistosity is only rarely seen on a very small scale and is strongly crenulated and largely transposed to s_2. S_1 is also occasionally seen as a fine metamorphic banding which has been preserved in narrow bands enclosed in the s_2 foliation and forming a slight angle to it (Fig.18).

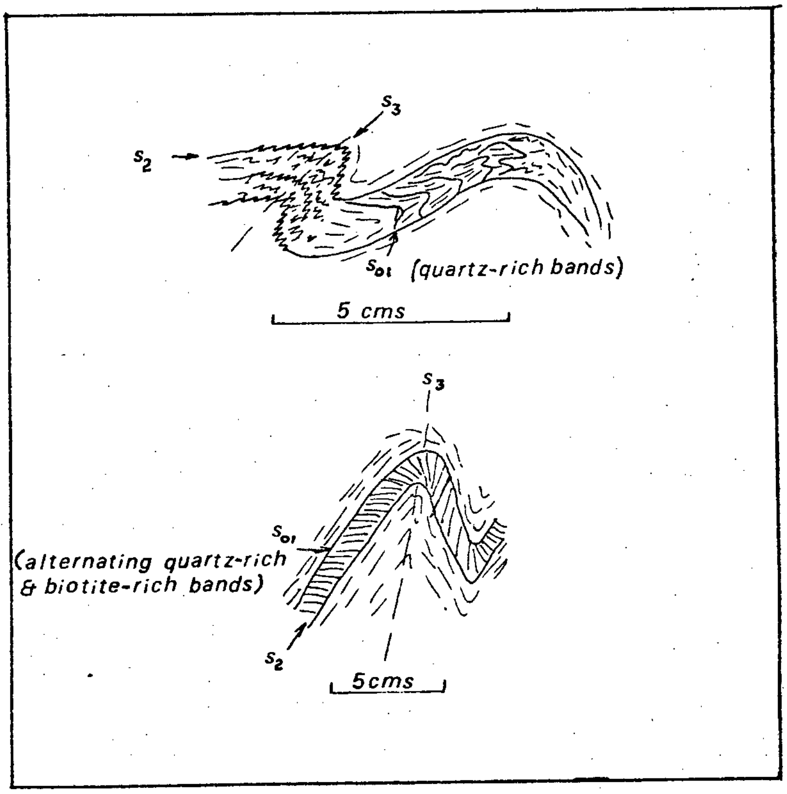


Fig.18. Fine metamorphic banding representing s_1, transposed by s_2 (subzone I.D.)

s_2 : The major biotite foliation in this area which forms the regional schistosity is also parallel to the tectonically developed compositional layering and is recognised as s_2. Mesoscopic features, indicative of a transposition foliation enclosing folded relicts of s_0 and s_1 (Fig.18 & 6d), are fairly commonly seen.

s_4 : A relatively narrow zone of intense crenulation foliation traverses the schistose rocks in the northern part of this section (7I), in a north-easterly direction. Dip is north-west and slightly steeper than s_2. A sheet of *G6* granite is intrusive into this zone.

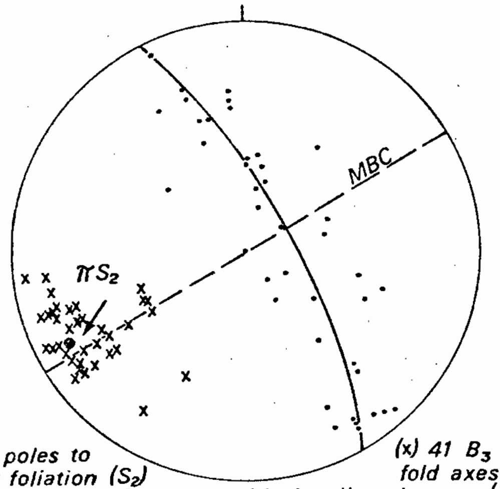
(ii) *Linear elements*

A very fine mineral lineation was occasionally seen on more quartzitic layers and is most likely to be l_2, considering the penetrative nature of s_2 in this area, however sufficient orientation measurements could not be obtained in order to develop a clear picture of relationships.

l_4 : Towards the southern boundary of this subzone there is an indication that B_4 crenulation structures have been superimposed on the east north-east trending very big open folds of B_3, as reflected in the plots of a few l_4 crenulation lineations measured on gently south-dipping schist (Fig.17).

(b) Mesoscopic structures

A number of examples of small, rootless, intrafolial fold closures were seen in this section, many of which are tightly appressed, however no final conclusion could be drawn as to whether they are B_1 or B_2. A few examples of slightly larger isoclinal folds of calc-granofels layers, having rounded hinges, occur in the vicinity of the band of quartz-amphibole schist (8I). These folds clearly have the major biotite foliation (s_2) as their axial plane foliation and are recognised as B_2. These folds, with amplitudes of up to 15 m, deform the composition bands which are only 5 to 10 cm thick and give rise to the tectonically formed compositional layering seen in most exposures.



(·) 41 poles to major foliation (S_2)

(x) 41 B_3 fold axes

MBC= orientation of metamorphic banding cleavage (Zone II)

Fig.19. Structural data for subzone ID.

B_3 : The effects of the deformation giving rise to these folds, first becomes apparent in the north of this section as the major foliation (s_2) changes orientation from shallow dips in a northerly direction to horizontal and then shallow dips to the south. Thereafter, progressing southwards, this foliation forms big, open, concentric folds which are characterised by the development of very small, crenulation-like concentric folds on the undulating surface (Plate 4). These folds all have a consistent orientation with a maximum at approximately 240°/12° (Fig.19). The stereographic plot of poles to s_2 in subzone I.D. define a great circle with π axis in the same area (Fig.19).

An axial plane foliation is not associated with these folds which are symmetrical and have near vertical axial planes, however, the associated very small folds have axial planes which fan outwards from the macroscopic axial planes (Plate 4).

At the southern boundary of subzone I.D. these folds become slightly asymmetrical and have a steeper south limb which is near vertical.

(c) Macroscopic structures

B_3 : No macroscopic B_3 folds can be definitely identified in this subzone but it appears that the mesoscopic B_3 folds described above, increase in size towards the south and reach macroscopic scale towards the southern boundary of the subzone.

The band of quartz-amphibole schist (*Sw2A*) (8I) is seen in the field to lie in the core of a macroscopic B_3 synform.

6. Relationship of quartz-sillimanite nodules to fabric elements

Quartz-sillimanite nodules are most commonly encountered in quartzo-felspathic gneisses and felspathic quartzites of the Etusis Formation. Most nodules have a tri-axial ellipsoidal form and have been found in various orientations with their orientation obviously related to the various deformation phases. Unfortunately, they are not easily extracted from their matrix in either the gneisses or the quartzites for the purpose of measurement of dimensions with the result that initial ideas of attempting a size-shape analysis of these features was abandoned due to the time factor involved.

Nodules most commonly occur in the relatively homogeneous gneisses of the Etusis Formation where they are most commonly orientated with their A-B planes parallel or sub-parallel to the stratiform foliation (s_{01}) and the A-axes parallel to the mineral lineation seen on this foliation in the surrounding rocks.

In the critical hinge zone of the Waldau Ridge antiform in subzone I.A. it could not be conclusively seen whether the A-B planes of nodules were orientated parallel to s_2 or s_{01}, although a few outcrops of felspathic quartzite in this area show that the A-B planes may be parallel to either s_1 or s_2, possibly depending on whether s_2 was penetrative or not at the particular locality.

In subzone I.B., rather more spherical nodules were seen to be slightly flattened parallel to the axial plane of B_3 in the cores of mesoscopic folds and equally slightly elongated parallel to B_3 axes. Earlier formed nodules in this vicinity (i.e. A-B parallel to s_{01}) have been deformed about B_3 axes (Fig.12a).

In some places nodules, which were originally orientated with A-B parallel to s_{01}, have obviously undergone re-growth so that they now lie with A-B parallel to the north-east trending minor shear zones (s_4(I.B.)) (Fig.20). In such cases there is not much elongation parallel to mesoscopic fold axes and the nodules commonly have axial dimensions A=B>C.

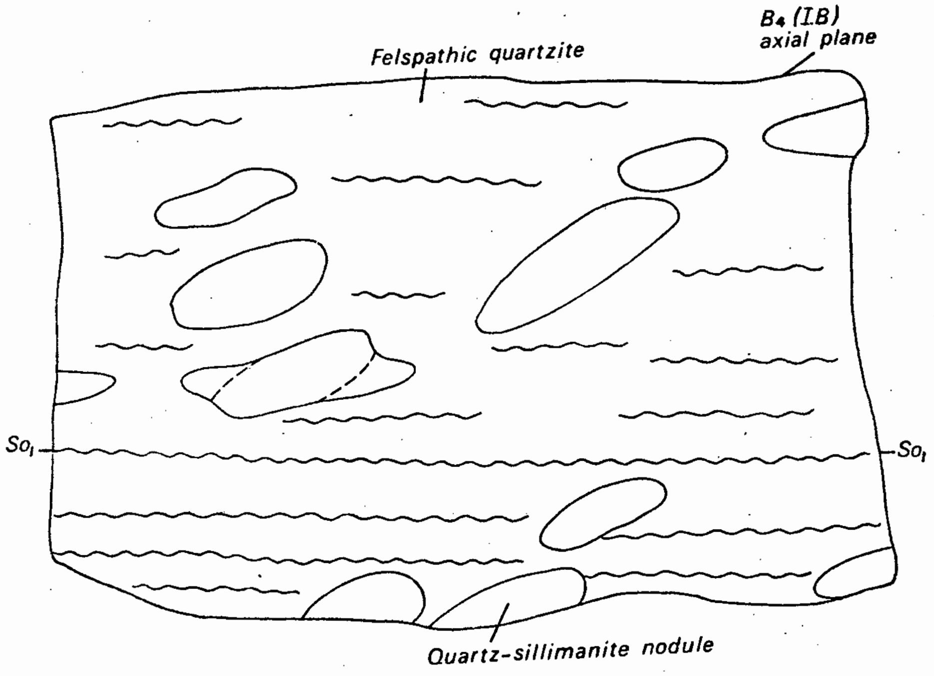


Fig.20. Sketch from hand specimen showing re-growth of quartz-sillimanite nodule parallel to axial plane of B_4(I.B.)crenulations. (Natural scale).

7. Zone II (Waldau River section-south)

This zone was traversed by the southern half of the Waldau River section (9I-12H)(Fig.3). The boundary between Zone I and Zone II was not precisely located in the Waldau River but lies in an unexposed area between the southernmost outcrops showing the features described in subzone I.D. above and the northernmost outcrops showing the features to be described below. On aerial photographs the boundary can be recognised as the northern limit of a zone of extremely fine linear features trending in an east north-easterly direction.

Rocks in this zone, are all of the Kuiseb Formation and consist of a homogeneous succession of quartz-biotite schists showing only occasional compositional variation, but characterised by the occurrence of a number of porphyroblastic minerals (cordierite, andalusite, sillimanite, muscovite) as well as spindle-shaped, calc-granofels bodies.

(a) Fabric elements

All the fabric elements encountered in Zone II can be seen in the vicinity of the hot spring area, near the Gross Barmen farmhouse (12H). However, the important features, which relate to the correlation of certain structures between Zone I and Zone II were found only in the Waldau River section, north of the hot springs.

(i) *Planar elements*

s_0 : Compositional banding is not obviously present in these rocks due to the intense penetrative development of later planar elements. Nevertheless, an almost horizontal and gently undulating compositional layering is present in these otherwise homogeneous rocks, which is accentuated by the preferential growth of certain porphyroblastic minerals in layers of suitable composition (up to 20 cm thick) (Plate 5). A further feature, although not as obvious, is the similar occurrence of layers of calc-granofels bodies (spindle- and torpedo-shaped) defining the original compositional variation. This near horizontal compositional layering was first recognised by Hälbich (1970) who referred to it as "bedding", however, in the absence of further indicative features of primary sedimentary origin, the writer prefers to use the annotation s_0 rather than ss.

s_1 : The most conspicuous secondary planar feature in these fine-grained rocks in this zone, is the penetrative development of very closely spaced fine lamellae, 0,5 to 2 mm wide, of alternating micaceous and siliceous material. This "metamorphic banding cleavage" (Hälbich, 1970) is near vertical and is equivalent to the feature mistakenly described by Gevers (1963) as "bedding lamellae" from this area (Hälbich, 1970). The relationship between metamorphic banding s_1 and s_0 can be seen in Plate 5 and the geometric relationships clearly indicate that the metamorphic banding cleavage is essentially axial planar to upright folds in the compositional layering (Fig.21a).

Close examination of outcrops reveals that most penetrative development of s_1 as a metamorphic banding is confined to compositional layers which have an intermediate biotite content while in layers which are more biotite-rich this segregation is not mesoscopically developed and the rock has a generally schistose appearance. Nevertheless, the biotite occurs as short subhedral flakes orientated sub-parallel to s_1, also the anhedral granular, quartz matrix is usually somewhat flattened. Lens-like segregations bounded by biotite-rich folia, which are typical of s_1 and s_2 foliation in similar rocks in Zone I, are not found. Refraction of cleavage between layers of differing composition is commonly observed with the result that in biotite-rich layers, s_1 is nearly

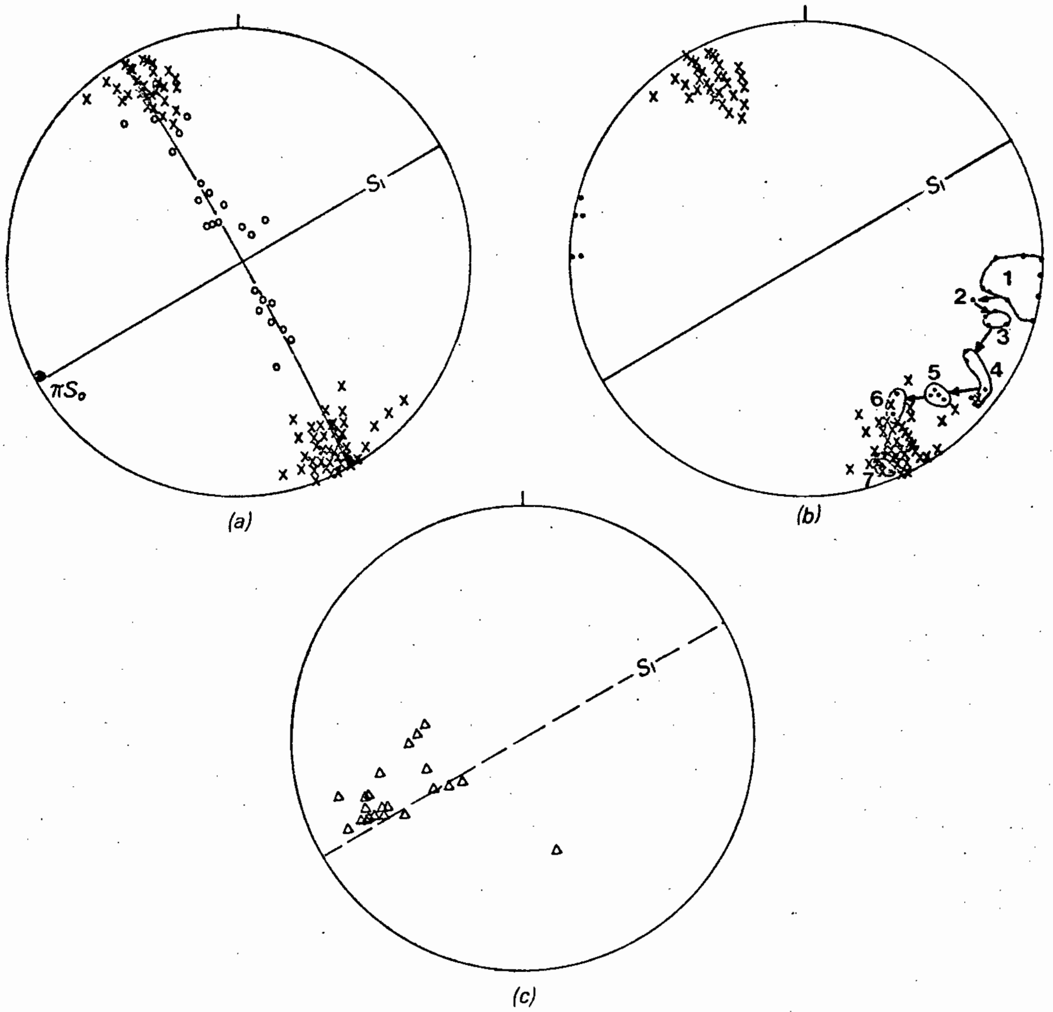


Fig. 21 . Structural data for Zone II
a) d_1(II) phase: (o) 24 poles to compositional layering, (S_0)
(x) 72 poles to metamorphic banding cleavage, (S_1)
b) d_2(II) phase: (·) 35 poles to crenulation foliation, (S_2)
(x) 72 poles to metamorphic banding cleavage, (S_1)
c) d_2(II) phase: (Δ) 21 intersection lineations S_1/S_2

parallel to the axial plane of associated small folds, while in more quartzitic layers the cleavage fans outwards from the hinges of these folds.

Calc-granofels bodies exhibit extreme flattening parallel to s_1 with axial ratios of the order of :- A:B:C = 5:11:1 where A is the intermediate, B the long and C the short shape axis (Hälbich, 1970). There is some evidence which indicates that these bodies may in part be the hinges of minor folds whose limbs have been thinned and removed by metamorphic differentiation. Although most examples seen indicate that the bodies originally formed discrete layers, there is some evidence particularly where isolated bodies occur, which suggest that they were originally in the form of nodules or concretions which later were flattened during deformation as proposed by Porada (1973).

Cordierite porphyroblasts, 1 to 3 cm in diameter have grown in some of the schistose rocks seen along the Waldau River in Zone II. These porphyroblasts commonly display rotational textures (Plate 7), particularly in the northern parts of Zone II, where they are also better developed than in the vicinity of the hot springs. S_1 can be traced through the porphyroblasts with the naked eye and can be seen to be sharply curved in the vicinity of these crystals. The sense of rotation of these porphyroblasts and the curvature of the foliation indicates clockwise rotation in the horizontal plane in all cases. Under the microscope, cordierite is seen to contain an internal foliation (s_i) which is not significantly curved. The s_i foliation is continuous with the external foliation (s_e) and is sharply curved immediately outside the boundaries of the porphyroblast. Weakly developed pressure shadows can be seen in some sections which consist of a thin selvage of coarser-grained anhedral quartz and some K-felspar, than the remainder of the s_e fabric (Plate 7). Fibrolite clusters occur as lens-like segregations and commonly show pressure shadow features in the form of slightly coarser-grained, quartz fabrics forming a curved "tail" parallel to s_1.

The cordierite porphyroblasts have grown over s_1 and in the northern part of Zone II it appears to be this same foliation along which right-lateral movements have occurred causing clockwise rotation of these porphyroblasts and curvature of s_1 in the immediate vicinity thereof.

s_2 : The well exposed area of the Gross Barmen hot springs displays numerous examples of this north north-east trending crenulation foliation, which was described in great detail by Gevers (1963), who referred to it as "fracture cleavage".

The intensity of penetrative development of this foliation is directly related to the biotite contents of layers which it traverses, as was the case with s_1 and can be clearly seen in Plate 8, together with the refraction of this foliation between layers of differing biotite content. Some metamorphic segregation occurs in suitable layers with the development of a new compositional banding on a millimetre scale.

Under the microscope, biotite, originally parallel to s_1 can be seen to be distinctly crenulated and re-orientated sub-parallel to s_2.

Gevers also described the myriad growth of elongate andalusite porphyroblasts orientated with their long axis parallel to s_2. These porphyroblasts have been extensively altered and now consist of a felted mass of white mica.

Both the crenulation foliation (s_2) and the andalusite porphyroblasts can often be found not directly associated with folds of the same generation.

Northwards from the hot springs the orientation of s_2 progressively changes (Fig.21b) until from a location only 2 km north of the hot springs, to the northern boundary of Zone II, there is very near parallelism of s_1 and s_2. Commonly, the only difference is that of dip but which is steeply north in both cases.

This re-orientation of s_2 from striking slightly east of north to striking slightly north of east, through an angle of approximately 60° indicates clearly a clockwise rotation (Fig.22).

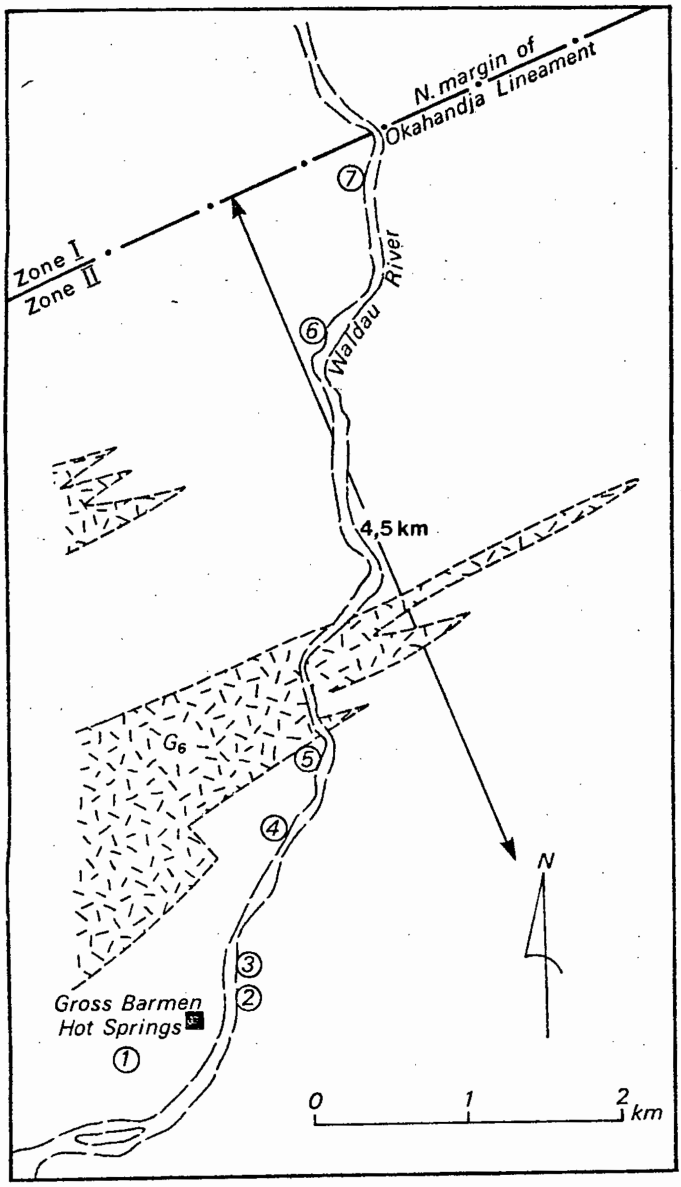
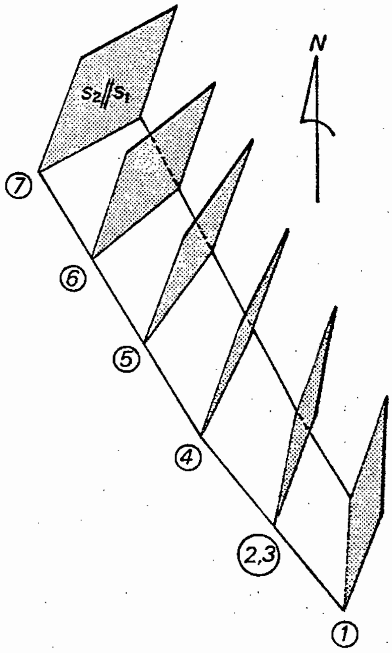


Fig. 22. a) Location of data groups in Fig. 21 b.



b) Schematic representation of rotation of S_2 in Zone II

(ii) *Linear elements*

l_1 : The intersection of s_1 with s_0 gives rise to a fine linear feature on s_0 planes. The extreme elongation of calc-granofels bodies (as described earlier) is the most commonly seen lineation and parallels the intersection lineation.

l_2 : The intersection of s_2 with s_1 is less commonly seen due to the non-penetrative nature of s_2 (Fig.21c). The elongation of andalusite porphyroblasts does not seem to relate to this intersection or to the intersection between s_2 and s_0 except where the latter is horizontal or sub-horizontal everywhere it is seen. Towards the north of Zone II a prominent lineation is evident on dip surfaces of s_1, which appears to be a result of weathering out of the pressure shadow area either side of rotated cordierite porphyroblasts. This linear feature dips westward at steeper angles than the fine lineations as seen on more quartzitic bands. The latter being the intersection lineation between s_2 and s_1.

(iii) *Mesoscopic structures*

B_1 : The compositional layering in the vicinity of the hot springs can be clearly seen to have been deformed into upright, big, open folds which are horizontal or plunge at less than 10° to the west south-west (Fig.21a). Although not readily apparent in this area these folds may be slightly asymmetric with antiforms having steeper limbs to the north, as found by Hälbich (1970) near Okahandja. On this scale the B_1 folds have concentric forms.

Approximately 1 km north of the hot springs, in the Waldau River an outcrop was found which shows smaller folds, but which is important for the interpretation of more regional relationships. At this site (Plate 6), very small, crenulation-like, concentric folds, are developed on gently undulating compositional bands. Where the metamorphic banding cleavage (s_1), axial planar to these folds, is most intensely developed, transposition of limbs of these folds has occurred and the rootless hinges which remain, have a more similar form somewhat akin to the B-C profiles of calc-granofels bodies commonly observed further south.

B_2 : In his study of the Gross Barmen hot springs area, Gevers (1963) described and depicted in great detail, the characteristic features of chevron-like, minor folds having generally north north-easterly trending axial planes, which he called "drag folds". The characteristics of these folds were not re-investigated in detail except in respect of their orientation. Their most common occurrence is as relatively isolated, small, chevron-like concentric folds with close, angular or rounded hinges. The inter-limb angle is noticeably in the region of 90° and the folds most commonly occur as associated pairs of antiforms and synforms resembling "kink bands". The form is most clearly outlined by the metamorphic banding cleavage and less commonly by the compositional layering where this is near vertical (Plate 8).

The plunge of these folds seen is entirely dependant on the dip of s_1 or as less commonly seen, s_0. However, few measurements could be made due to the nature of the exposures; therefore B_2 and l_2 have been combined in Fig. 21c.

(c) Macroscopic structures

B_1 : Symmetric, big, open folds and near horizontal compositional layering at Gross Barmen hot springs was taken by Hälbich (1970) to indicate that a macroscopic synformal axis passes through this area (Gross Barmen synform - Fig.3). Northwards from the hot springs area one clearly passes into the south-dipping limb of a major synform as the compositional layering steepens to become near vertical in places and the s_1 foliation changes orientation to dip

steeply northwards, while immediately south of the hot springs area, s_1 dips steeply to the south. This relationship confirms that the fold trace through Gross Barmen hot springs is synformal as the metamorphic banding cleavage fans downwards away from the hinge, thus repeating on a large scale a similar phenomena commonly seen on a small scale.

Hälbich (1970 - Plate XIV) depicted these large folds in his interpretive sections as being very big, upright, open to close folds and having rounded hinges. They are characterised everywhere by axial planar, west south-west/east north-east (240°/060°) trending near vertical, metamorphic banding cleavage.

Precise definition of these folds on a large scale is however, hampered by the large scale homogeneity of the Kuiseb Formation.

C. Kinematic Interpretation

Discussion of the relationships of the various deformation phases in the Waldau area can be divided into "early" & "late" phases, relative to regional foliation s_2. Those phases of deformation which pre-date this foliation or were responsible for the development thereof are termed "early" and those which post-date or deform this foliation are termed "late".

The proposed correlation of phases in each subzone and their overall relationships which will be discussed below is shown in Table 3.

		Zone I				Zone II
		I.A.	I.B.	I.C.	I.D.	
Early	D_1	d_1 (I.A.)	d_1 (I.B.)	d_1 (I.C.)	d_1 (I.D.)	
	D_2	d_2 (I.A.)	d_2 (I.B.)	d_2 (I.C.)	d_2 (I.D.)	
Late	D_3		d_3 (I.B.)	d_3 (I.C.)		
	D_4				d_3 (I.D.)	d_1 (II)
	D_5	d_3 (I.A.)	d_4 (I.B.)	d_4 (I.C.)		d_2 (II)

Table 3. Correlation of deformation phases (d) in various subzones and relationship to deformation phases (D) recognised for the area as a whole.

1. Early phases of deformation in Zone I

(a) D_1 Phase

The earliest phase of deformation in Zone I is recognised with varying degrees of certainty in different areas depending on the intensity of the phases which post-date it. Certainly, it is easiest to recognise this phase in the rocks of the Karibib Formation where intrafolial, isoclinal folds with angular hinges occur between bounding planes of similar composition to that which is folded, particularly in subzones I.A., I.B., and I.C. Close examination of outcrops in subzone I.D. as well as in some areas in subzones I.A. and I.B. is quite often rewarded by the discovery of a biotite or biotite-fibrolite foliation (s_1) which is deformed by B_2 folds or the penetrative development of s_2.

Biotite and fibrolite formed in the lower Etusis metapelites at this time, as well as in the quartzo-felspathic members of the Etusis Formation, essentially as a bedding foliation, at the base of and within the competent mass of quartzo-felspathic rocks, while being developed as an axial planar foliation to B_1 folds at higher levels in less competent rocks.

In subzone I.A. the relationship between macroscopic B_1 and B_2 folds is complicated by lithologic variation due to facies changes as well as later granite intrusions, nevertheless the relationships as interpreted in Fig.8 indicate a fairly high angle between B_1 and B_2 axes. Similarly in subzone I.B. the axes of B_1 folds make a high angle with that of the macroscopic B_2 axis.

The original orientation of macroscopic B_1 folds appears therefore to have been with axes trending slightly west of north, approximately parallel to the present day orientation of B_1 folds along the west flank of the Waldau Ridge structure (Fig.23).

(b) D_2 Phase

The Waldau Ridge antiform is the only macroscopic representative of the D_2 phase in this area. Examination of the two reclined hinges of this structure, in subzones I.A. and I.B., has shown that a characteristic feature of this deformation was the development of a macroscopically penetrative axial planar foliation and the transposition of earlier planar fabrics in suitable rock types, mainly the Kuiseb Formation. Penetrative development of s_2 on the mesoscopic scale was directly related to the proportion of competent lithotypes (eg. quartzite) in the other formations.

Although the eastern hinge of this structure has been disorientated from its post-D_3 orientation by still later deformation it is clearly possible to recognise that the Waldau Ridge antiform was initially a major recumbent fold whose axis probably trended parallel to the regional trend of the Abbabis Swell (i.e. east north-east) and which verged towards the south.

The D_2 phase, Waldau Ridge antiform, was considerably larger than folds of the D_1 phase, while also involving Etusis and pre-Etusis rocks to a greater

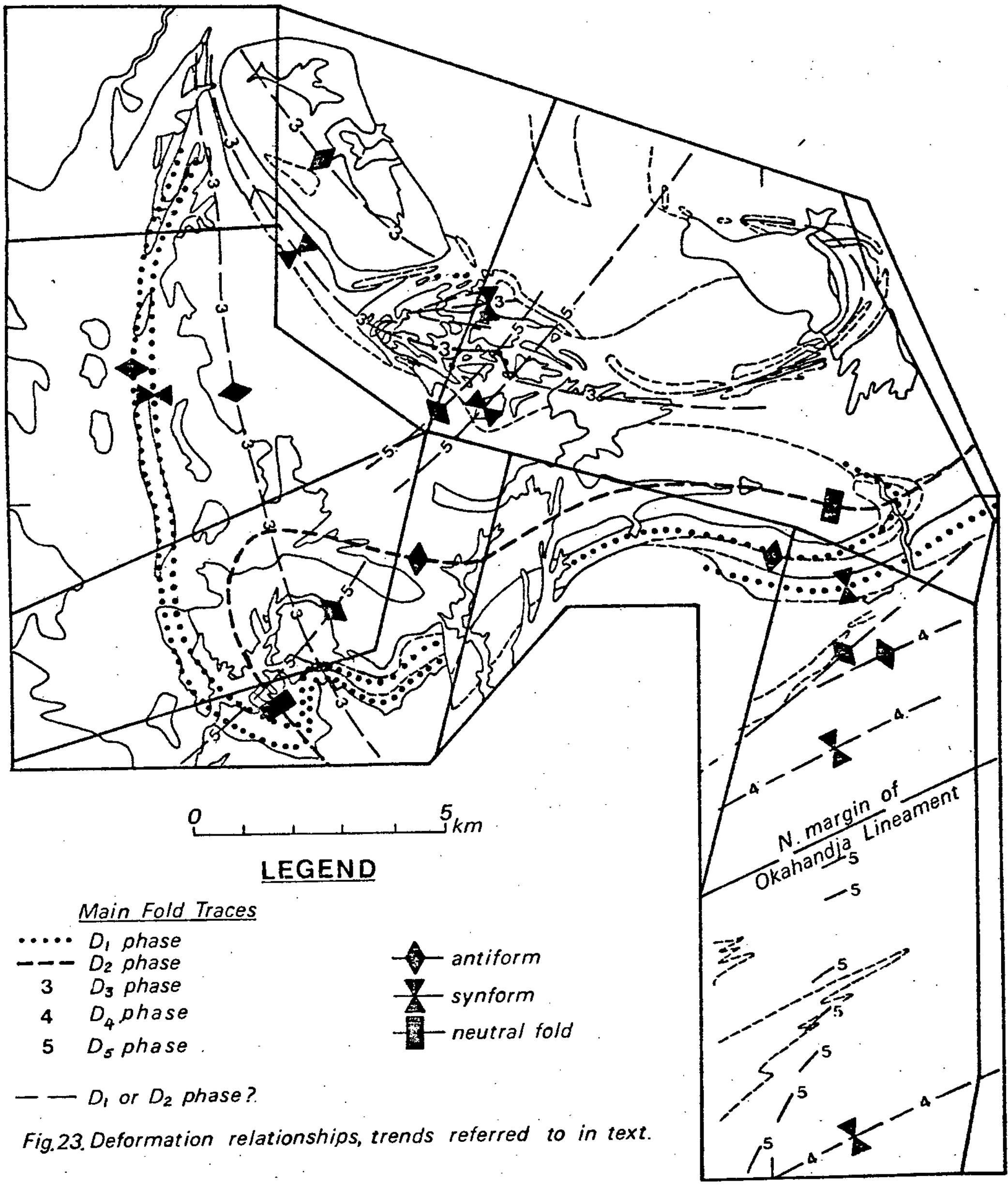


Fig.23. Deformation relationships, trends referred to in text.

extent than D_1. This is shown by the fact that no D_1 phase folds of any size can be recognised in most of the Etusis rocks. Considerable tightening of B_1 folds probably occurred during this deformation, although no direct evidence was found, with the result that the axial planes of B_1 folds became parallel to the limb of the larger B_2 fold (Fig.24).

2. Late phases of deformation in Zone I

(a) D_3 Phase

The effects of this deformation are not seen everywhere in the area, as

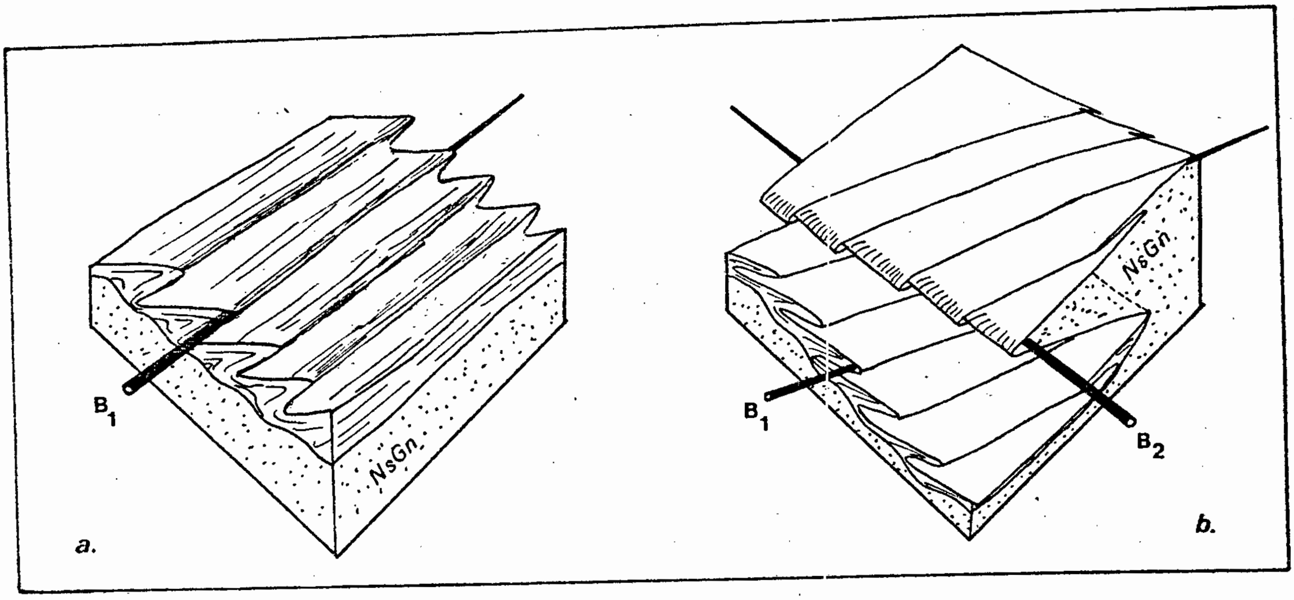


Fig.24. Structure block diagrams showing relationship between D_1 and D_2 phase deformation.

a penetrative planar fabric is not associated with B_3 folds as described in subzones I.B. and I.C. Correlation of this phase from these two subzones is based on their corresponding geometric character while the apparently opposite plunges of the Löwenberg antiform and the Ritter synform can be clearly seen to be related to the original orientation of the limbs of the southward recumbent Waldau Ridge antiform. The Löwenberg antiform being developed on the overturned lower limb and the Ritter synform was developed on the normal upper limb of this B_2 fold (Fig.25). Once again it is apparent that later deformation (D_5) has extensively affected the orientation of these folds particularly the Ritter synform, nevertheless it appears that the axial planes of the Löwenberg antiform and the Ritter synform converged along the west side of the Waldau West structure.

The essential form of the Waldau Ridge structure can be interpreted as being due to the interference pattern produced by superimposition of the upright B_3 Löwenberg antiform onto the southward recumbent Waldau Ridge antiform The resultant pattern, although somewhat distorted by D_5 deformation, can be equated to the Type 2 interference pattern of Ramsay (1967) or more specifically that derived when $\alpha = 90^\circ$ and $\beta = 0^\circ$ (Ramsay, *op.cit.*, p.513).

The Waldau West structure is believed to have been a corresponding B_3 antiform which plunged in the same direction as the Ritter synform but which has been extensively affected by later (D_5) deformation. The interference of B_3 and B_5 in this case having given rise to an interference pattern of Type I i.e. $\alpha = 90^\circ$, $\beta = 90^\circ$ (Ramsay, *op.cit.*, p.513).

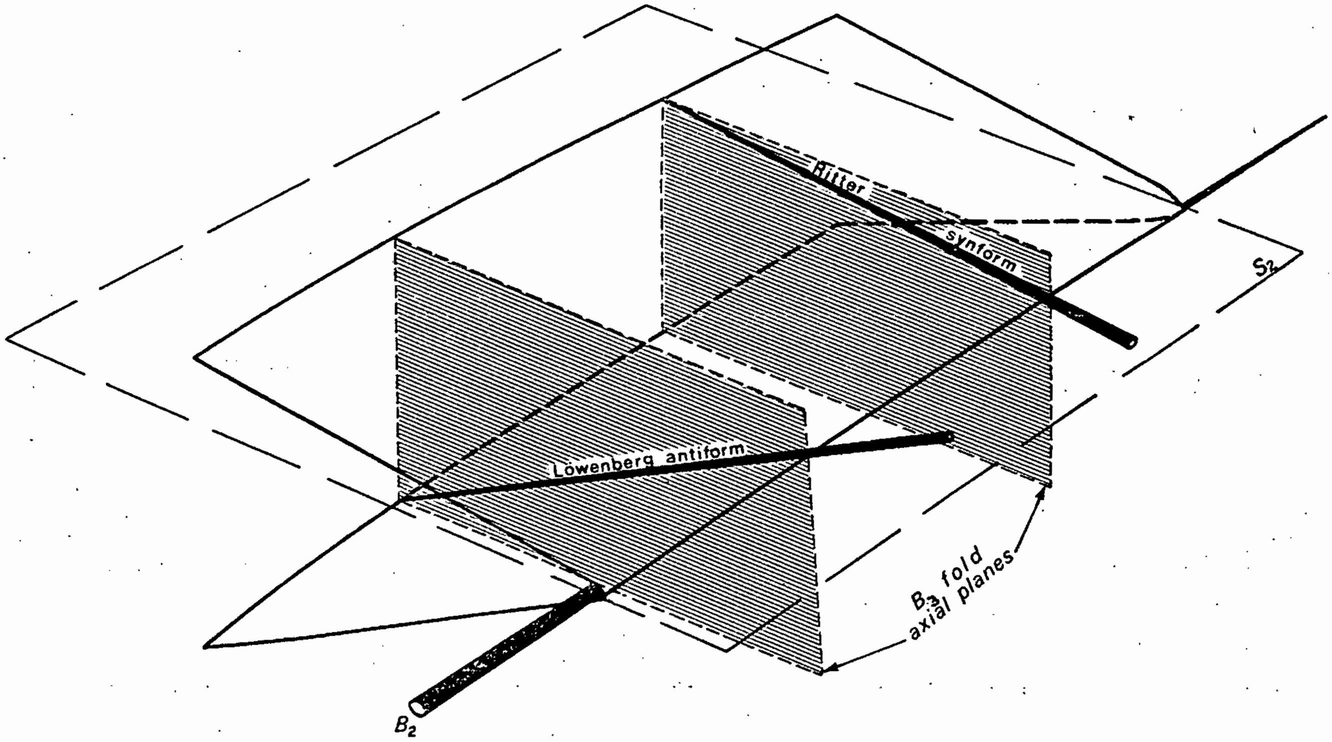


Fig.25. Diagrammatic representation of relationship of plunges of B_3 - folds to limbs of recumbent B_2 (Waldau Ridge antiform)

(b) D_4 Phase

In Zone I, deformation assigned to this phase is recognised only in subzone I.D. (d_3(I.D.)) and as can be seen there, the effects of this deformation decrease towards the north and are not recognised north of 8T. Therefore, there is no conclusive evidence in the area represented by the geological map, to prove that d_3(I.D.) in fact post-dates the deformation concluded above to represent D_3 in the area as a whole. Granite intrusion obscures relationships between d_3(I.B.) and d_3(I.D.), as was found during reconnaissance mapping in the area south of subzone I.B.

(c) D_5 Phase

This deformation was the easiest to define and although the type of deformation varies according to lithology, the consistent north-easterly trends of related structures have been superimposed on all earlier structures throughout Zone I. Mesoscopic and macroscopic features ascribed to this deformation phase, indicate either left-lateral or right-lateral movement in the horizontal plane. It was not possible to define the actual movement necessary to bring about the reorientation of the eastern hinge of the Waldau Ridge antiform from a plunge in an east north-east direction (after D_3) to that of north north-west as seen at present. Macroscopic axial plane traces of D_5 folds are concluded to trend from the south-west corner of the Waldau Ridge structure through the eastern part of subzone I.C. (Fig.23).

The curvature of the macroscopic B_2 axial plane at the eastern hinge of the Waldau Ridge antiform - which necessitated the subdivision of subzone I.A. into more homogeneous domains - shows a fold axis which plunges parallel to the hinge of the Waldau Ridge antiform (Fig.9) rather than towards the north east as shown by the mesoscopic B_5 fold axes in this vicinity (Fig.17). This deformation of s_2 is due to the proximity of a macroscopic D_5 fold which trends in a north-easterly direction across the northern part of Gross Barmen and the south-eastern part of Waldau West (Fig.23).

3. Correlation of late phases of deformation between Zones I and II

The most significant feature to bear in mind in this connection is the fact that the compositional layering in Zone II has been found to be primary and is probably bedding, which shows no evidence of having been affected by the three phases of deformation - D_1, D_2, D_3 - recognised in Zone I.

(a) D_4 Phase

The common orientation of folds of d_3(I.D.) and d_1(II) (Fig.19, 21a) is regarded as being a strong point in favour of their correlation, particularly considering the close proximity of the areas in which they are found. The overall style of the folds in these two phases is likewise very similar (compare Plates 4 and 6). The development of a penetrative metamorphic banding cleavage which essentially defines the axial planes of small folds of d_1(II) while a similar metamorphic differentiation is not seen associated with small folds of d_3(I.D.), is believed to reflect the primary nature of compositional layering deformed by d_1(II) (see section IV. D.).

(b) D_5 Phase

The d_2(II) deformation clearly forms part of the D_5 phase as recognised in Zone I by virtue of the common orientation (Fig.17) and the style of deformation. It is believed that the form of these folds in Zone II and the reorientation of their axial planes (Fig.21b, 22) are indicative of right-lateral movement in the vicinity of the boundary between Zone I and II or an anti-clockwise rotation of Zone I relative to Zone II.

4. Correlation of deformation history in the Waldau area with other parts of the Damara Belt

Structural studies from various parts of the Damara Belt have made abundantly clear the poly-phase nature of the deformation which affected it (Fig. 26). Possible correlation and relationships discussed here will be concerned largely with the findings of other workers in the regions of the Abbabis Swell and the Khomas Trough.

Smith (1961) and Roering (1961) were two of the earlier workers to apply

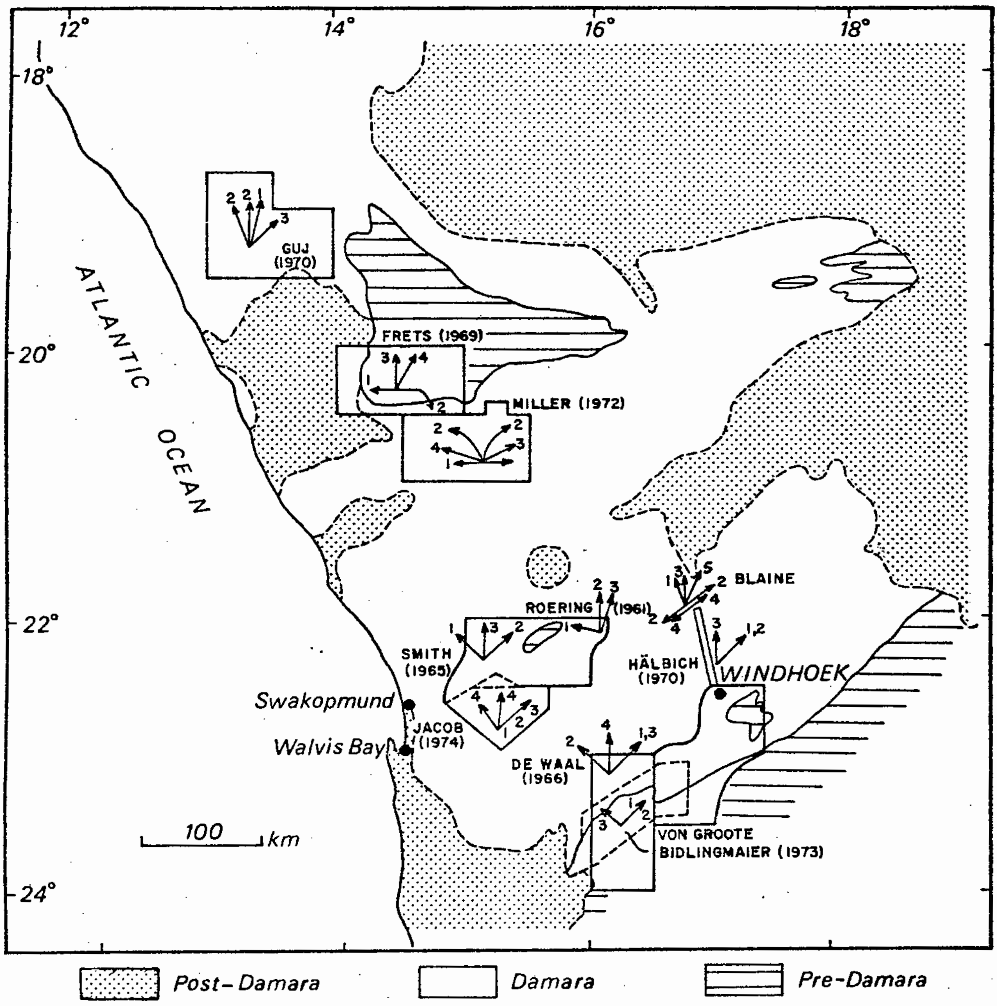


Fig. 26. Map showing reported fold trends in the Damara Belt. Fold phases listed chronologically in each area. Arrows indicate fold trends. Geology modified after Martin (1965).

modern techniques of structural analysis to the Damara Belt and in particular the Abbabis Swell, in the Khan-Swakop area. Both these workers recognised the earliest folds in this region as having trends in the north-west quadrant. Jacob (1974) working in much the same area failed to confirm this north-westerly orientation and recognised the earliest folds in his area as having had north-easterly trends and ascribed this variation to the control exerted by pre-Damara basement, as proposed by Frets (1969) and Miller (1972).

The possible north-west trends for the earliest structure in this region correspond with conclusions drawn from the present area for the D_1 phase. However it is similarly recognised that the form of pre-Damaran basement may have exerted a local control over orientation of these earliest folds in some areas.

The trends of the major fold structures in the Abbabis Swell is clearly north-east as found by Smith (*op.cit.*) and Jacob (*op.cit.*) while Roering (*op. cit.*) in a very small area found no major folds corresponding to this trend. Although the major north-east trending folds described by these workers have essentially upright axial planes it is significant to note that these folds become markedly asymmetric with steeper limbs to the south along the southern margin of the Abbabis Swell and steeply north-dipping axial planes, which perhaps indicates that these folds might become progressively more overturned and finally recumbent in regions slightly further removed from the rigid basement core of the Abbabis Swell or at slightly higher structural levels than those exposed in the Khan-Swakop area, studied by Smith (*op.cit.*) and Jacob (*op.cit.*).

Later, open structures with northerly trends and lack of or only local development of penetrative planar fabrics are reported by both Smith (*op.cit.*) and Jacob (*op.cit.*) from this region.

Hälbich's (1970) synthesis of the structural history of the Khomas Trough showed that the earliest folds in this region were upright and had north-easterly trends parallel to the regional framework. The axial planes of these folds were described by him as having been progressively transposed, towards the south by a macroscopically penetrative, north-dipping foliation which owed its origin to the overriding mass of a huge southward moving nappe structure whose roots are now represented by the granitic core of the Abbabis Swell (Hälbich, *op.cit.*, Plate XIV).

There is clear evidence in the Waldau area that the major phase of deformation (D_2, this study) which was proposed by Hälbich (*op.cit.*) to have given rise to the huge southward moving nappe envisaged by him, in fact pre-dates the earliest upright folds recognised by him (D_4, this study). Furthermore, this major phase of deformation is believed to pre-date even the deposition of the majority of rocks exposed in the Khomas Trough.

The late north-east trending phase (D_5, this study) of deformation which is generally characterised by crenulations post-dating all previous structures is similarly not macroscopically penetrative throughout the area studied by Hälbich (*op.cit.*) and may not be represented (Smith, 1965) or have more variable orientation locally (Jacob, 1974; De Waal, 1966).

D. Dynamic Interpretation

The present investigation of the Waldau area has brought to light or emphasized the existence of many features which indicate the presence of a major linear feature (Okahandja Lineament) forming the southern boundary of the Abbabis Swell. The major features of the tectonic history of this area are believed to be related to the movement history of the Okahandja Lineament.

The role of "lineament tectonics" (Hills, 1963) in the structural geological history of many areas is well known and the observation that major linear zones of tectonic activity may remain so, through extended periods of geologic time, is well documented (Watterson, 1975). The observed characteristic of such features as the expression of a persisting mechanical weakness, means that a lineament is likely to accommodate a variety of movement directions during its active life, as well as being the locus of both brittle fracture and ductile simple shear strain in the upper and lower levels of the crust, respectively (Watterson, *op.cit.*).

1. Recumbent folds

The recognition of the D_2 phase as a major period of recumbent folding places important constraints on the causes of the deformation in the area during this time. Recumbent folds may essentially be generated by either gravity gliding or by low-angle thrusting.

In most examples of gravity gliding, mesoscopic features are indicative of local inhomogeneities within the rocks involved in the gliding (Kröner, 1974b). The variable orientation of mesoscopic axial planes probably indicates the lack of confining stress in the system. Most examples of macroscopic recumbent folds in the literature appear to be related to nappe formation with single macroscopic folds having overturned limbs in excess of 5 km (Ramsay, 1967; p.359) in length. Similarly, experimental work shows the development of macroscopic recumbent folds, as nappes (Bucher, 1956) as essentially thin-skinned deformation at supra-crustal levels, in a state of pure shear. Evidence from the Waldau area shows the existence of highest metamorphic grades during formation of the recumbent Waldau Ridge antiform, with pressures of some 400-450 MPa (see Chapter V) indicating depths of burial of some 15 km. This is inconsistent with a model of thin-skin deformation at high crustal levels, at this time.

Low-angle thrusting as a means of forming recumbent folds, is less well documented. A recent paper describes the development of a recumbent isoclinal fold above the Shikoku Subduction Zone of south-west Japan (Moore and Karig, 1976), essentially as a result of the simple shear couple acting along the thrust plane. Amplitude in this case is some 1,5 km. There is some evidence in subzone I.A. that low-angle thrusting did occur locally and gave rise to the narrow zones characterised by quartz eyes and ribbon-like granular quartz segregations, essentially parallel to the axial planes of mesoscopic D_2 folds, but possibly slightly later than the main D_2 phase.

In the Waldau area, it appears possible that the vertical movements, parallel to the southern margin of the Abbabis Swell, active during the depositional phase (see Chapter III), resumed or continued into the deformational phase, thus establishing a gravity gradient in this marginal zone between the Abbabis Swell and the Khomas Trough. The macroscopic recumbent Waldau Ridge antiform is believed to have been initiated under the influence of gravity and high confining stress. Hence the extensive development of penetrative planar fabrics parallel to the axial plane of the fold. Movement was directed towards the Khomas Trough, either due to uplift in the Abbabis Swell or continued subsidence of the Khomas Trough. Local, low-angle thrusting appears to have occurred slightly later in the D_2 phase, but does not seem to be responsible for the actual development of the recumbent fold.

2. Competency differences

It is significant to note that no D_1 folds were recognised in the homogeneous quartzo-felspathic mass of the Etusis Formation and that s_1 developed in these rocks forms a bedding foliation. Similarly this deformation did not affect the underlying Abbabis Complex. This style of deformation is similar to that described by Guj (1970) for the earliest folds recognised by him in the south-western Kaokoveld (Fig. 26) which trended parallel to the north northwesterly branch of the Damara orogen in this region and were characteristically non-basement involving, indicating that peak metamorphic grades had not yet been reached (Fig. 24a).

However, during the D_2 phase maximum metamorphic grades had been attained (see Chapter V) with the result that the homogeneous quartzo-felspathic mass of the Etusis Formation and the underlying Abbabis Complex had become "softened up" to the extent that they both became involved in the D_2 phase deformation (Fig. 24b).

During the D_4 phase the rocks in the southern part of Zone I were apparently not as tightly folded as those in Zone II and the folds diminish in size and die out rapidly towards the north in Zone I. It is believed that this feature reflects the more competent nature of the rocks in Zone I which had become tectonically consolidated by an intense period of tectono-thermal activity, prior to deformation during the D_4 phase, whereas the rocks in Zone II had not undergone this event.

3. Selective development of s_4, and the possible origin of the metamorphic banding cleavage

It has been stressed that planar element deformed during the D_4 phase is significantly different in the southern part of Zone I to that in Zone II. The rocks in Zone I had been involved in probably three phases of intense deformation and high-grade metamorphism, whereas those in Zone II had not undergone any deformation prior to D_4, therefore these sediments undoubtedly contained significant quantities of water which probably facilitated the metamorphic differentiation necessary to give rise to the metamorphic banding cleavage (s_4).

It is significant to note that the intense penetrative development of s_4 is confined to an extremely linear zone some 25 km wide whose southern limit appears to be formed by the extremely linear escarpment of the Khomas Hochland which overlooks the valley of the Swakop River (Fig. 2). This foliation apparently becomes less penetrative and is confined to narrow zones (10-30 cm wide) along the southern margin of this zone. Similar features to these seen in Plate 6 have been interpreted as being due to homogeneous flattening (Hobbs, *et.al.*, 1976, p.256) which is supported by thin sections of the fine-grained quartz-biotite schist from Zone II which show some flattening of the quartz fabric.

No mesoscopic or microscopic features (Bell and Etheridge, 1973) were found in the limited area studied, which could undoubtedly be recognised as being characteristic of mylonites. Considering the likely original composition of the rocks in Zone II as having been homogeneously fine-grained sediments, it would be surprising if some of the characteristic features of mylonitisation of coarser-grained rocks such as "porphyroclasts", were evident in these rocks. It is believed more likely that metamorphic differentiation acted instead, as suggested by Vernon (1974).

The flattened and spindle-shaped calc-granofels bodies might be described as mesoscopic porphyroclasts, or be essentially similar to the flattened and rotated "pipes" in Cambrian quartzites described by Johnson (1967), who interpreted the banding in mylonites as being a surface of "flatteningstrain".

It is therefore suggested, that the zone of penetrative development of metamorphic banding cleavage (s_4) might represent a zone of "flatteningstrain", localised by the proximity of the relatively rigid Abbabis Swell and the presence of a fundamental zone of weakness, which forms the Okahandja Lineament as seen at present.

4. D_5 deformation as the result of right-lateral movement along the northern margin of the Okahandja Lineament

Gevers (1963) first proposed the existence of a zone of right-lateral movements in the vicinity of the Gross Barmen hot springs in order to explain the formation of the minor fold structures in this vicinity, described by him as drag-folds (d_2(II), this study). However, a number of other features are present in the Waldau area which indicate the existence of such a zone of right-lateral movement marking the boundary between Zone I and II. These features are recognised as:

(a) the trends of B_5 folds and s_5 planes in Zone I;

(b) the sense of displacement and orientation of faults and fractures in subzones I.B. and I.C;

(c) the trend and sense of rotation of s_5 planes in Zone II, with respect to the orientation of the northern margin of the Okahandja Lineament.

The right-lateral movement has apparently, in this case given rise to "drag-fold" and fracture patterns (Moody and Hill, 1967; Wilcox *et.al.*, 1973) as well as ductile shear strain phenomena (Ramsay and Graham, 1970). "Drag-folds" are an important feature associated with wrench faulting, as shown by Moody and Hill (*op.cit.*) and form at an angle of approximately 15° to the wrench fault. Complementary faults and fractures of decreasing orders of magnitude are recognised by Moody and Hill (*op.cit.*) as forming at set angles according to the fault classification system of Anderson (1951). Simple shear models by Wilcox *et.al.* (*op.cit.*) produced a pattern of :

(a) en-echelon folds inclined at low angles to the wrench zone;

(b) conjugate strike-slip faults;

(c) the main wrench fault parallel or sub-parallel to the wrench zone and (d) normal faults or tension joints orientated perpendicular to fold axes.

The structural features of the area which lend themselves to the application of the "drag-fold" and fracture pattern model are shown in Fig.27, together with the appropriate terminology of Moody and Hill (*op.cit.*) and Wilcox *et.al.* (*op.cit.*). The primary first-order wrench (right-lateral) is deduced as being essentially parallel to the boundary between Zone I and Zone II and to the mesoscopic axial planes of D_4 folds. In the model of Wilcox *et.al.* (*op.cit.*) the wrench fault itself only develops in a late stage of the whole process, when as much relative movement as possible has been taken up by "drag-folds" and other associated features. It is therefore possible that a single plane of displacement is not present at this boundary. The "antithetic" fractures in Fig.27 have been obtained from Gevers (1963) (who recorded minor fractures and faults with this trend) who related them to the fracture pattern derived by right-lateral horizontal movements.

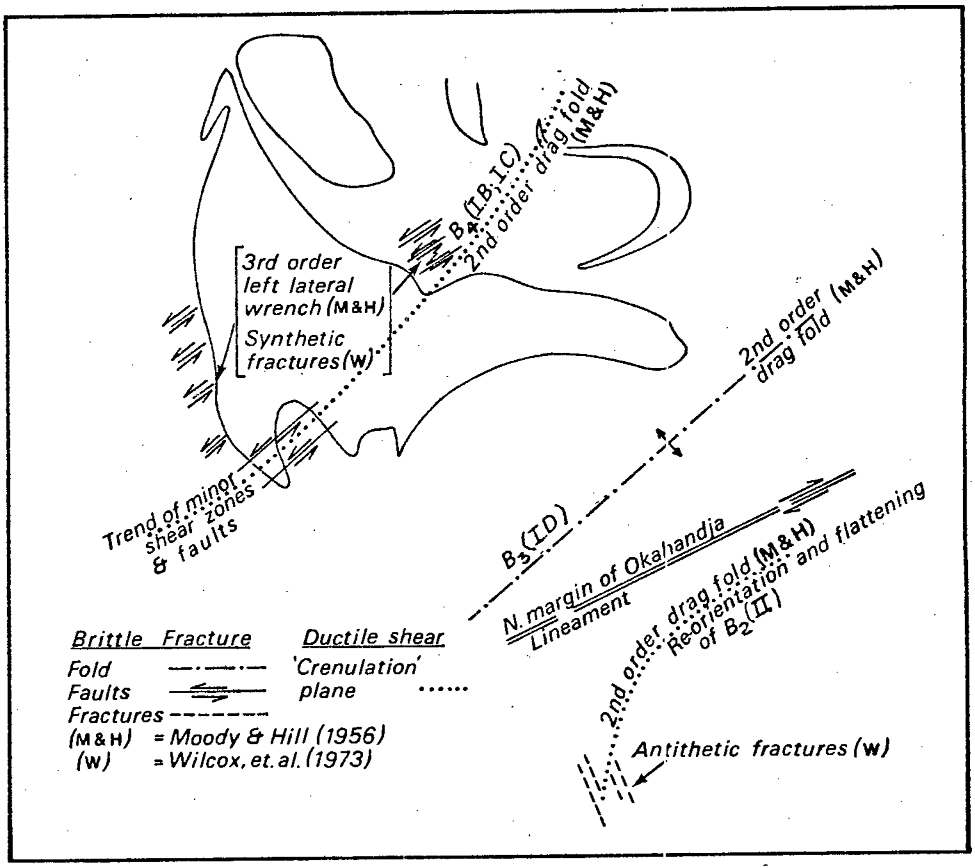


Fig.27. Features of the Waldau area probably related to large scale, right-lateral, strike-slip movement along the northern margin of the Okahandja Lineament.

The application of a ductile shear model (Ramsay and Graham, 1970) is aimed specifically at the mesoscopic and microscopic rotational features described in Zone II as well as the mesoscopic asymmetric D_5 folds (Plate 3) in Zone I, commonly found in the quartzo-felspathic rocks of the Etusis Formation. These folds indicate the existence of maximum P-T conditions in the area at the time of their formation with the development of pegmatitic neosomes in the planes of "maximum shear". The sense of movement along these planes is left-lateral in all cases and is consistent with that shown by wrench faults commonly seen in the Karibib Formation rocks in subzones I.B. and I.C. These mesoscopic D_5 folds (Plate 3) and the associated planes of "maximum shear" are essentially identical to features described by Toogood (1976) as being minor shear zones associated with the Pofadder Lineament, a feature shown by him as having resulted from deformation by ductile shear strain. Features of the area pertinent to a ductile shear model are shown in Fig.27.

The crustal levels at which either brittle fracture or ductile shear occurs in rocks are commonly described as upper and lower respectively. However the boundary between the regimes of brittle fracture and ductile shear may be better defined in terms of the P-T conditions at a particular site, rather than conditions at a particulat crustal level (Brace and Byerlee, 1970). The P-T conditions of such an arbitrary division of crustal levels seems most likely to be related to normal lithostatic pressures and geothermal gradients rather than the conditions of increased pressure and temperature encountered in zones of deformation.

The rheological properties of rocks may be influenced by a number of parameters, the most important of which are:

(a) the confining pressure;
(b) the strain rate;
(c) the temperature;
(d) the nature of the chemical environment (Ramsay, 1967).

Experimental work by Griggs and Handin (1960) showed that practically all rocks investigated at 500°C and 500 MPa showed ductile deformation. The 700 MPa maximum confining pressure placed on the brittle behaviour of rocks at room temperature by Edmund and Murrell (1973) might be considerably reduced with increased temperatures, as the yield point between brittle and ductile deformation is lowered by higher temperatures (Heard, 1960; Brace and Byerlee *op.cit.*). The P-T conditions in the Waldau area have been determined as being in the region of 650°C and between 400-500 MPa (Chapter V), this corresponds very closely to the boundary between brittle and ductile deformation as defined experimentally. In such a position it may be expected that local characteristics such as rock composition and pore pressure (Brace and Byerlee *op.cit.*) might determine whether the rock behaved in a brittle or a ductile manner.

It is proposed, therefore, that the favourable rock composition in the case of the homogeneous, quartzo-felspathic portion of the Nosib Group and the greater pore pressure in the younger sediments of Zone II made possible the more ductile deformation shown by these rock units during the D_5 phase.

E. Structural relationships of the igneous rocks

Essentially all the igneous rocks in the Waldau area were emplaced during the Damara Orogeny. Their relationship to the tectonic activity during this period renders a classification in terms of "tectonic category" (Wynne-Edwards, 1969; Jackson, 1976) possible. This classification could be made more specific and also more complex by definition of time of emplacement in respect of individual deformational phases. If it is considered that the five phases of deformation recognised in this area were part of a single complex tectonic event, however, subdivision can be in terms of "syntectonic" and "post-tectonic" only. The distinction of "early" and "late" in the syntectonic category, can be made relative to the time of formation of the major foliation (s_2), as previously discussed. The relationships of igneous intrusions, in the post-tectonic category, to thermal conditions makes it possible to distinguish "early" and "late" post-tectonic events. Those intrusions displaying no contact metamorphic effects being "early" and those which do show contact metamorphic effects, being "late", as it has been recognised that peak metamorphic conditions outlasted the deformation.

The G1 granitic rocks were emplaced early in the D_2 phase, are strongly foliated and show the effects of maximum metamorphic grades. The field evidence shows that these bodies were emplaced as dykes essentially parallel to the major B_2 axial plane yet contain the s_2 foliation and are therefore classified as "early syntectonic".

The Salem Granite is regarded as being largely the *in situ* product of ultrametamorphism of Kuiseb Formation schists, in synformal structures (Smith, 1965; Jacob, 1974). Anatexis occurred during a period of maximum metamorphic grades and only marginally does this rock unit show relict D_1 or D_2 fabric elements. Development probably spans the "syntectonic" category.

The G2 granite shows only weakly the effects of the D_3 phase and D_5 phase deformations. It is intrusive into parts of the Salem Granite and can be classified as "late syntectonic". There has apparently been no contact metamorphism.

The body of orthopyroxene-bearing gabbroic rock intrudes the G2 granite and is apparently not affected by the D_3 phase. It is similarly not noticeably deformed by the later D_5 phase and shows some weak effect of retrogression, but whether this is related to M_1 or M_2 (see Chapter V) is not known. It is therefore regarded as probably belonging to the "late syntectonic" category.

The G3 granite was not found in contact with any of the other igneous rocks except as dykes cutting G2 and is undeformed with no contact metamorphic effects. The emplacement relationship with the north-east trending faults indicate that this granite intruded either late in the D_5 phase or after it, but during the period of maximum temperatures and emplacement is therefore classified as "early post-tectonic".

The G4 and G5 granites are closely related in space and time with both forming irregular bodies showing no structural control. Field evidence shows the intrusive relationship of G5 with G4. G4 and G5 granites intrude all members of the Damara Supergroup in this area as well as pre-Damaran rocks and post-date D_5 structures.

In the northern parts of the Waldau Ridge Structure there is strong evidence for *in situ* development of some G5 granite from quartzo-felspathic rocks of the Etusis Formation. No contact metamorphic effects are shown by either of these two granitic types, indicating emplacement during the period of maximum temperature, and therefore belong to the "early post-tectonic" category.

The Donkerhoek Granite (G6) in the Waldau area is part of the easternmost extremity of a large north-east trending elongate batholith (Fig.2). It has been emplaced largely into the zone of "flattening strain" which is the present surface expression of the Okahandja Lineament. Contact metamorphic effects associated with bodies of this granite indicate that emplacement was after the period of maximum metamorphic grades (M_1). Intrusion apparently occurred during a later regional, thermal metamorphic event (M_2) (see Chapter V), the granite is therefore classified as late "post-tectonic".

F. Post-Damara Structures

A number of relatively minor structural features occur in the Waldau area which cannot be related to the Damara Orogeny. A number of north-south trending major faults occur which are especially evident on a large scale in the centre and south-western parts of the Waldau Ridge structure. Vertical movements have been accommodated along these faults, giving rise to apparent horizontal displacement in the northward dipping, southern edge of the Waldau Ridge structure. In the centre of this structure a poorly exposed, triangular area of Abbabis Complex rocks is interpreted as being a small horst block. The major bounding fault on the north side of this block is considered to be responsible for the narrow linear, partly sand-filled valley which parallels the contact between the Etusis Formation and the Swakop Group immediately to the north-west of the horst.

In the Waldau River (7I) a number of north-south trending faults occur, having brecciation and slickensiding associated with them, as well as some local warping of the schist. These faults produce offsets in the north-dipping body of Donkerhoek Granite in this area. In the homogeneous, quartzo-felspathic rocks of the Nosib Group which cross the main road on Waldau (2F), a number of thin (1-3 mm wide) seams of very fine-grained, dark brown amorphous material - which may be pseudotachylite - form a north-south, west-east network.

A series of north-south trending faults displacing Karoo sediments by vertical movements are a feature of the shallow basin of Karoo sediments some 50 km north of the Waldau area (Geological map of South West Africa, 1963). Similarly, post-Karoo faulting is believed to be responsible for the north-south trending graben extending across the Khomas Hochland from Windhoek towards Okahandja.

Interpretation of ERTS-1 and conventional aerial photographs indicate that the southward continuation of the major post-Karoo fault to the north of the Waldau area continues to the west of the Waldau Ridge structure and the possibility exists that the sand-choked Ozombanda River valley may in part be a graben similar to that traversing the Löwenberg antiform. Local information indicates that the sand in this valley is up to 60 m deep in places (Wagner, personal communication). The numerous fracture-traces shown on the geological map and interpreted from aerial photographs, including offsets of the steeply north-dipping body of Donkerhoek Granite near Gross Barmen hot springs, are interpreted as being related to these fault movements. Some thin dolerite dykes were found to be related to these linear features.

North-south trending mesoscopic features in the form of fissures filled with brecciated material have been described from the Gamsberg (Fig.1) by Wittig (1976) who attributed their formation to intense seismic activity related to the breaking apart of Africa and South America during the late Mesozoic. It is considered most likely that the north-south trending and related linear features in the Waldau area can be similarly related to this event.

V

METAMORPHISM

The Waldau area is similar to those areas studied further west (Smith, 1965; Nash, 1971; Jacob, 1974) in the sense that the rocks have undergone high-grade metamorphism and in places, anatexis. The mineral assemblages in rocks of this area fall within the amphibolite facies of Turner (1968) or the low-pressure amphibolite facies of Miyashiro (1973).

A. Carbonate and siliceous-carbonate rocks

The marble, calc-granofels (Jackson, 1976, p.21), calc-quartzite and quartz para-amphibolite lithotypes are confined to the Swakop Group. Large thicknesses of pure marble bands are rare in this area and generally contain variable proportions of calc-granofels bands. Dolomite, which was distinguished from calcite by staining (Wolf *et.al.*, 1967), is the major constituent of the fine-grained, white marble bands, interlayered with schist on the northern part of Gross Barmen. Dolomite is apparently subordinate to calcite in the more siliceous lithotypes, probably due to the near completeness of the reactions:

(1) 5 dolomite + 3 calcite + 2 quartz + 1 H_2O = 1 tremolite + 3 calcite + 7 CO_2 followed by:

(2) 1 tremolite + 3 calcite + 2 quartz = 5 diopside + 3 CO_2 + 1 H_2O
or:

(3) 1 dolomite + 2 quartz = 1 diopside + 2 CO_2 (Winkler, 1974)

Major constituents in the calc-granofels and calc-quartzite lithotypes are quartz, diopside, tremolite and pale green-brown amphibole with lesser amounts of calcite, dolomite, sphene, plagioclase and chlorite. Compositional banding in these rocks is largely defined by varying proportions of quartz and diopside/amphibole. These minerals make up bands which are folded, as well as those which are axial-planar to big folds. This tends to indicate that suitable metamorphic conditions for the progression of the above reactions existed from slightly prior to the onset of deformation.

Hoffer and Puhan (1974) studied samples from Rudenau North and Waldau and have recognised the parageneses:

(4) diopside + tremolite + calcite + quartz

(5) forsterite + tremolite + dolomite + calcite

from which they constructed the "clinopyroxene" isograd based on the reaction (2). This isograd was located by them as trending in a north-easterly direction through Gross Barmen.

Paragenesis (5) was not seen in any of the specimens from the present area.

The very pale-green to pale-brown amphibole is commonly found replacing diopside along cleavage planes or enveloping it poikiloblastically. This mineral is especially common in the dark coloured quartz para-amphibolite bands occurring on Gross Barmen and the characteristic basal quartz para-amphibolite of the Karibib Formation in this area.

B. Pelitic and Quartzo-felspathic rocks

Specimens of metapelite from the Kuiseb Formation were collected at places along the Waldau River. Elsewhere in the Waldau area, this rock type is either not exposed, or extensively weathered. Specimens of pelitic rocks from the lower and upper members of the Etusis Formation were also examined. The varieties collected are fine-grained schistose rocks which are occasionally porphyroblastic. Quartz and biotite are the most common constituents with varying lesser amounts of sillimanite, K-felspar, andalusite, muscovite, garnet, cordierite, white mica and chlorite. Quartzo-felspathic lithotypes are confined to the Etusis Formation and sillimanite in quartz-sillimanite nodules, is the only metamorphic index mineral developed in these rocks.

1. Zone I

The major foliation in Zone I is due to the strong parallel alignment of *biotite*. This can either be s_1 or s_2, depending locally on the degree of transposition of s_1 by s_2. This biotite was formed during D_1 and D_2 with some re-growth during the later phases of deformation. Biotite is commonly retrogressively altered to *chlorite* and is sometimes interleaved with *muscovite* which is present co-existing with quartz in a prograde assemblage. Porphyroblasts of muscovite as larger (2 mm), unorientated flakes and chlorite as nests of "cross-mica" occur in many specimens.

Sillimanite, generally as fibrolite, is the most common metamorphic index mineral throughout the area. In the quartzo-felspathic rocks of the Etusis Formation, it occurs only in quartz-sillimanite nodules while in the schistose rocks, sillimanite occurs as ovoid nests of fibrolite enclosed in the biotite foliation. Quartz-sillimanite nodules are the subject of a comprehensive study by Losert (1968) who concluded that these nodules were the product of conditions of localised de-alkalisation which occurred "after the main tectonic movements and metamorphic crystallisation had ceased", a mechanism supported by Macauderie and Touret (1969). Many of the relationships described by Losert (1968) were found in this area. Earliest-formed nodules are related to the stratiform foliation in the Etusis Formation, are well flattened and lie sub-parallel to it. Elongation is largely parallel to l_2. During D_3 almost spherical to slightly flattened nodules grew in new sites over the pre-existing foliation, while early well-flattened nodules were bent (Fig.12a). Finally, re-growth of pre-existing nodules in NsGnl and NsuS & Q occurred during D_4 (Fig.20) and are strongly inclined to s_{01} & s_2. Flattening occurs parallel to the axial-planes of B_4 folds. There is undoubtedly some compositional control on location of nodules in the Waldau area, particularly as shown by the nodular sillimanite gneiss unit of NsGnl. Similar nodules commonly occur in Gl granite on Waldau and are flattened parallel to the biotite foliation and the oblique cleavage across this rock. The observation that the nodules in all cases have grown over the foliation generated at the respective times is in accordance with Losert's (1968) conclusions. The orientation of flattening and elongation shows that they have a definite relationship to and slightly post-date, specific tectonic phases.

K-felspar is developed as porphyroblasts on Waldau in many of the schistose rocks (Sw2S) in the northern part of the area and commonly gives rise to "dents de cheval" texture. On Gross Barmen the only other similar occurrence of this mineral was noted where small (1-2 mm), porphyroblasts of microcline show slight rotation with respect to the external biotite foliation, concluded to be s_2, as the porphyroblasts have a weakly developed internal foliation also of biotite flakes. White mica is a common minor constituent, occurring as fine-grained felted masses largely as a retrogressive alteration product of fibrolite.

Garnet was not observed in hand specimens and only one thin section contained a small (less than 1 mm), skeletal aggregate illustrating post-tectonic (s_2) growth. No cordierite was found in the specimens from Zone I, nor was it's presence suspected from field examinations.

2. Zone II

In Zone II the major foliation is due to a sub-parallel alignment of small, euhedral *biotite* flakes set in a matrix of somewhat flattened, granular quartz and arranged in fine laminae 0,5-2 mm wide of alternating biotite-rich and quartz-rich bands. This essentially defines the metamorphic banding cleavage (s_1(II)), characteristic of the monotonous pelitic and semi-pelitic rocks in this area. Biotite was folded and some re-growth took place during the D_5 phase (s_2(II)).

Sillimanite as fibrolite occurs as small (1-2 mm) clusters, apparently post-dating s_1, in the vicinity of Gross Barmen Hot Springs. Further north in Zone II, similar material is more flattened in this foliation. Retrogressive alteration to white mica occurs extensively. Near spherical, quartz-sillimanite nodules occur in occassional narrow bands of quartzo-felspathic rock similar to Gl. Relationships are not clear, but the nodules appear to post-date s_1.

Cordierite, forming rounded porphyroblasts (1-2 cm in diameter), post-dating s_1, have been described by Hälbich (1970) from the area immediately south of Okahandja. Similar rounded porphyroblastic structures occurring in the vicinity of the hot springs and which now consist entirely of a fine-grained, felted mass of white mica, may be totally altered cordierite. Towards the north of Zone II cordierite becomes easily recongisable and considerably less "pinitised". These porphyroblasts similarly post-date s_1 and are notably helictic, showing a consistent right-lateral rotation. In many cases the cordierite is markedly xenoblastic, showing preferred growth at a high angle to s_1 (Plate 7).

Andalusite was reported by Gevers (1963) from this area as being elongated conspicuously parallel to the locally developed north north-east trending crenulation foliation (s_2), and to a lesser extent parallel to s_1. Gevers (*op.cit.*) included many photographs and a detailed description of the occurrence (Plates 5 & 8). Close examination of these porphyroblasts, which are now largely altered to white mica, shows that although maximum elongation is parallel or sub-parallel to s_2, growth has in fact occurred along the infinitely closely spaced metamorphic banding cleavage (s_1) defining an almost microscopic new compositional layering (Fig.28). As noted above, the porphyroblasts described by Gevers (*op.cit.*) as andalusite, are extensively altered and in thin sections no remnants of andalusite could be found in the specimens examined. Crushed fragments of one specimen, which appeared to be less altered, was identified as probably being andalusite (Malling, personal communication).

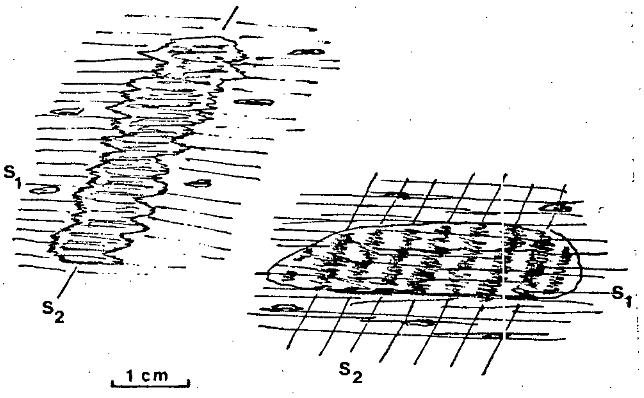


Fig.28. Sketch showing relationship between porphyroblast growth, s_1 and s_2 at Gross Barmen Hot Springs.

The occurrence of this andalusite in the form of elongated flat plates or rods, if it developed as a result of the contact metamorphic effect of the intrusion of the Donkerhoek Granite (Gevers *op.cit.*), rather than anhedral blasts, is surprising. If the andalusite is pseudomorphed after some earlier formed mineral, which normally has a long slender habit, however, then this type of occurrence may be more satisfactorily explained. It is proposed therefore, that during d_2(II), which is correlated with D_5 (Table 3) and with which sillimanite growth is known to be associated in Zone I, sillimanite also grew in Zone II parallel to the north north-east trending crenulation cleavage (s_2(II)) This development, which marks the end of the major period of metamorphism and deformation, was followed by a period of cooling in which the P-T conditions in the area would have moved into the stability field of andalusite. The Donkerhoek Granite is known to have been intruded post-tectonically (Faupel, 1974; Jacob, 1974; this study). This period of thermal metamorphism, imprinted on sillimanite, which at that time was possibly meta-stable in the stability field of andalusite, is believed to have brought about the re-crystallisation of sillimanite to andalusite in Zone II, in close proximity to the intrusions. The fluid phase possibly introduced into the system by the granite intrusion is not necessary for this re-crystallisation to occur (Miyashiro, 1973, p.39), although it is possibly assisted in the reaction. Further to the south-west a symmetrical thermal aureole represented by the growth of andalusite, with sillimanite closer to the contacts of the Donkerhoek Granite, has been found by Sawyer (personal communication) and is concluded to have been due to the superimposition of a thermal gradient onto rocks already regionally metamorphosed to amphibolite facies but after cooling below peak metamorphic conditions.

Garnet is rarely found and then as scattered small (0,5-1 mm), idioblastic, skeletal porphyroblasts and sometimes also occur as thin, single layers of tiny, red, crystals parallel to the mesoscopic compositional layering (s_0). *Muscovite* occurs commonly as sub-idioblastic and xenoblastic, unorientated porphyroblasts up to 2 mm in the length as well as smaller orientated flakes interleaved with biotite, sub-parallel to s_1 and co-existing with quartz in a pro-grade assemblage.

Spindle-shaped bodies consisting of a white, quartzo-felspathic matrix, studded with small red garnets and disorientated biotite, amphiboles and some diopside, have been described by Gevers (1963), Hälbich (1970) and Porada (1973) from this area. The minerals may be arranged in concentric shells parallel to the boundary of these bodies. Hälbich (*op.cit.*) concluded that these bodies formed by metamorphic differentiation during the formation of s_1 and that the regional amphibolite facies metamorphism just outlasted the deformation, hence the concentric zoning.

Porada (*op.cit.*) studied the same feature over a wide area and concluded that the segregations formed diagenetically and were subsequently deformed and metamorphosed.

3. Migmatites

Migmatisation related to the earlier phases of deformation, occurs sporadically in the eastern parts of the Etusis Formation and becomes more extensive in a westerly and north-westerly direction. Irregular segregations of granitic mobilisate occur generally parallel to the compositional layering in the east, while further west these quartzo-felspathic rocks contain extensively developed granitic mobilisate which is weakly foliated (s_2). The most extensive development of migmatite in both the Etusis Formation and the Swakop Group lies north-west of a line extending from 8C to 4I on the geological map. This line can be defined as the isograd "anatexis in gneiss" (Jacob, 1974). The modal composition of most of the quartzo-felspathic rocks examined from the Etusis Formation is equivalent to that of granite or alkali-felspar granite, when plotted on the triangular diagram for the general classification of plutonic rocks (Strekeisen, 1974) (Fig.4). This means that partial melting phenomena could be expected to be more widespread in these rocks than in the more pelitic Kuiseb Formation (Miyashiro, 1973, p.22).

C. Contact Metamorphism

Contact metamorphic effects are extremely rare in this area. Only the Donkerhoek Granite and it's pegmatites have had any noticeable effect on the country rock. Re-crystallisation of biotite into coarse-grained, unorientated flakes on the contact of pegmatite dykes with pelitic rocks is clearly evident on Gross Barmen.

On Otjiruse, dykes of Donkerhoek Granite pegmatite intrude the carbonate rocks of the Karibib Formation. Golf-ball size, garnet porphyroblasts (grossularite/ andradite?) have grown in these rocks in a zone approximately 5 m wide. Similar features are present in a carbonate-rich band crossing the main road on Waldau. In this case no Donkerhoek Granite occurs in contact or nearby, while the locally intruded granites are assigned to G2 and G5 types, neither showing contact metamorphic effects with carbonate rocks elsewhere in the area.

D. Discussion and Interpretation

No firm conclusions can be reached concerning the location of metamorphic isograds with respect to the Waldau area, partly due to the small size of the area studied. There is abundant evidence however, that the area lies totally on the high temperature side of the "sillimanite" isograd, defined by the reaction:-

(6) staurolite + muscovite + quartz = sillimanite + biotite + H_2O;

attained during the major period of regional metamorphism.

During the present survey it was seen and Gevers (1963, map) shows the occurrence of staurolite immediately south of the Swakop River (less than 1 km south of the mapped area).

Considering the macroscopic structure in this vicinity, it seems highly unlikely that the non-appearance of staurolite at the hot springs is due to unfavourable rock composition (Hoschek, 1969; Winkler, 1970). From previous discussions it appears likely that reaction (6) has gone to completion in the hot springs area and that the "sillimanite" isograd lies not far south of the mapped area. Hoffer and Puhan (1975), figured the isograd for "andalusite" and "sillimanite", marked by the reaction (6) and :

(7) staurolite + muscovite + quartz = andalusite + biotite + H_2O;

as crossing to the north of the Swakop River, a short distance west of Gross Barmen. The figured north-easterly trend of these isograds would mean that they bisect the farm Gross Barmen.

It is important to note at this stage that the isograds of Hoffer and Puhan (1975) are thought to be related to the youngest, post-tectonic, largely thermal metamorphic event affecting these rocks during the Damara Orogeny and it is also considered possible that this event is related to the period of intrusion of the Donkerhoek Granite. From the present observations, these isograds for the youngest metamorphic event, cannot be considered as correctly placed. The occurrence of andalusite in the vicinity of Gross Barmen hot springs is not ascribed to formation by reaction (7), but rather due to the direct inversion:

(8) sillimanite = andalusite;

from the aforegoing discussion.

Cordierite seen on Gross Barmen formed fairly late in the major period of regional metamorphism and its association with sillimanite in pelitic rocks is not abnormal (Miyashiro, 1973, p.211). Cordierite has been recognised as a reliable indicator of pressure, calculation of which is dependant on the determination of Fe^{2+}/Mg ratios in the mineral. Possible reactions for the formation of cordierite in this area are not known with certainty, but may be similar to those suggested by Jacob (1974):

(9) staurolite + muscovite + quartz = biotite + almandine + Al_2SiO_5+H_2O
followed by:

(10) biotite + Al_2SiO_5+ quartz (+Na-plagioclase) = cordierite + (K-Na felspar)
(Na-Ca plagioclase)
- garnet + H_2O.

Conditions for the formation of cordierite and garnet which apply here are probably similar to those recognised by Jacob (*op.cit.*) and that the formation of either or both depends on the Fe and Mg contents of the system and the prevailing pressure.

The establishment of the isograd "anatexis in gneiss" is clearly possible on the basis of field observation. The exact positioning is naturally dependent on rock composition with the result that some anatectic effects are noted in the quartzo-felspathic rocks to the south-east of the isograd. It is not known whether the isograd "K-felspar and sillimanite in anatectic gneiss" (Jacob, *op. cit.*) defined by the reaction :

(11) muscovite + quartz = sillimanite + K-felspar + H_2O;

is located in the Waldau area. Although reaction (11) was not observed, it is by inference likely that the pattern of isograds in the Waldau area is similar to that of the south-west where the "sillimanite + K-felspar" isograds lie on the high temperature side of the "anatexis in gneiss" isograd (Jacob, *op.cit.*). The probable P-T conditions applicable to the area investigated can be located with reference to reaction (6) and (11) and the anatexis in gneiss minimum (Fig.29). Pressure conditions were below those defined for the triple point for Al-silicate polymorphs due to the completion of the reaction (6) before the isograd of "anatexis in gneiss" is reached. Therefore P-T conditions were probably similar to those in the south-east of Jacob's (*op. cit.*) study area where temperature reached 650°C and pressures were between 400 and 500 MPa. The two high-grade metamorphic events postulated by Nash (1971) were concluded, after further investigation by Jacob (*op. cit.*), to have been compatible with a single prolonged metamorphic episode.

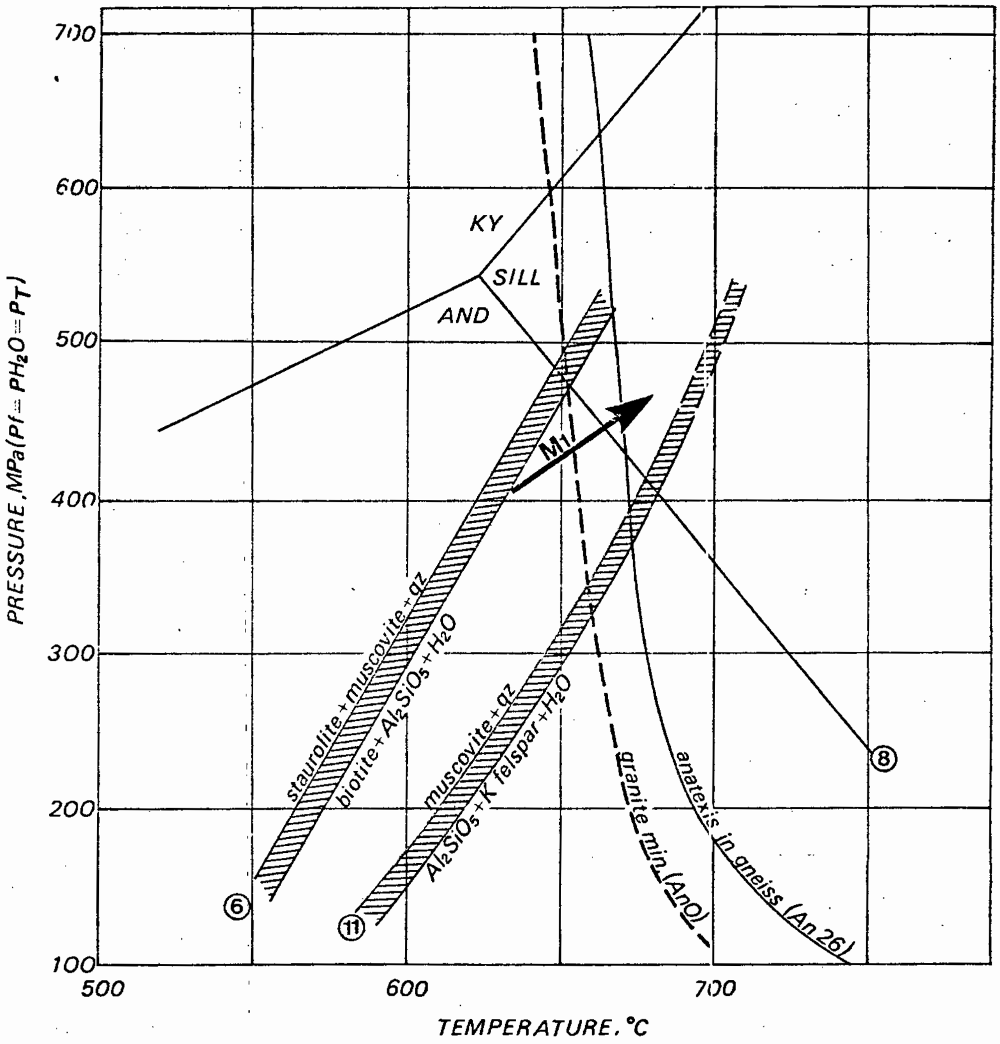


Fig. 29. Diagram showing probable M_1 P-T conditions in the area studied and some of the experimentally determined equilibrium curves for reactions mentioned in the text; eg. paragenesis (6) = aluminium silicate triple point after Richardson, *et. al.*, (1969)

Similarly then, in the Waldau area it is recognised that maximum metamorphic grades continue throughout the major period of deformation and in fact slightly outlasted it. This is shown particularly by the lack of contact metamorphic effects associated with the early post-tectonic granites (G3, G4, G5).

A later largely thermal event, brought about local re-crystallisation of sillimanite to andalusite, together with more widespread blastesis of muscovite. Extensive retrograde metamorphism also occurred and followed on this, resulting in the replacement of Al-silicates by white mica, chloritisation of biotite and amphiboles and pinitisation of cordierite.

VI

CONCLUSIONS

A. Local Events

The Waldau area is occupied largely by the easternmost known occurrence of Etusis Formation in the central, linear ge-anticlinal zone of the Damara Belt, known as the Abbabis Swell.

The stratigraphic and tectonic history of the Waldau area has been influenced to a large extent by movements associated with the Okahandja Lineament, which is recognised as a tectonic feature of regional proportion and significance.

1. The earliest expression of the Okahandja Lineament took the form of vertical movements, along the northern boundary of what was probably a major graben-like structure (proto-Khomas Trough). Shallow water clastic sediments are a feature of the lowermost parts of the Damara Supergroup along the Abbabis Swell, but there is strong evidence to suggest, however, that much of the quartzo-felspathic material in the Etusis Formation in the Waldau area may have originally been in the form of acid volcanic ash and/or lava outpourings. This volcanic activity could have been related to the contemporaneous vertical faulting and fracturing of the crust along this lineament. It is also possible that some of these rocks may represent an arkosic wedge deposit as has been found in many regions associated with areas of rapid uplift (Krumbein and Sloss, 1951). A hiatus in this Etusis volcanic activity occurred, during which fumarolic emanations gave rise to concentrations of iron, copper, zinc and sulphur. These metalliferous concentrations are recognised as a marker horizon transgressing the homogeneous sequence of the Etusis Formation in this area. Recognition of this marker horizon with its unique composition, is used as evidence for facies changes towards the south and south-west, causing interfingering of Etusis Formation and lowermost Kuiseb Formation lithotypes in this area. This transgression and rapid facies change is interpreted as indicating that deepening of the proto-Khomas Trough occurred during this period, probably with step-faulting (having downthrow on the south), progressing towards the north so that successively younger stratigraphic levels overlap onto the Abbabis Complex.

The shallow-water, carbonate deposition of the Karibib Formation also overlaps onto the Abbabis Complex on Waldau West, a local unconformity is evident in places and is interpreted as indicating further subsidence along this zone prior to deposition of the Kuiseb Formation. Carbonate-quartzite sequences were deposited south of the Waldau West basement and interfinger to the south and upwards with pure carbonate layers. The pure carbonate unit, in turn, soon interfingers with pelitic lithotypes in the same direction, and these in turn overlap onto the Abbabis Complex on Waldau West. It is probable that all units then became buried by the Kuiseb Formation, or higher units, the total thickness of which is unknown.

2. The approach of maximum metamorphic grades (amphibolite facies, M_1), was accompanied by compressive forces from the west, which gave rise to the D_1 phase of deformation. Tight similar folds, overturned towards the east, developed in the relatively incompetent sequences of the upper Etusis Formation and the Swakop Group.

3. M_1 metamorphism continued with the onset of compressive forces, perpendicular to the major trend of the Damara belt. The southward recumbent, east north-east trending Waldau Ridge antiform developed during the D_2 phase, possibly under the influence of a gravity gradient caused by relative uplift of the Abbabis Swell, or further deepening of the Khomas Trough. The continued vertical movement and associated fracturing of the crust may be reflected by the relatively narrow swarm of G1 dykes intruded largely parallel to the axial plane of the Waldau Ridge antiform. These rocks were foliated during this deformation.

Transposition of earlier planar structures occurred in suitable lithogies and was probably accompanied by tightening of D_1 folds, so that their axial planes became essentially parallel to the limbs of the D_2 fold.

Most field evidence indicates that the migmatisation of the Kuiseb Formation occurred and the bulk of the Salem Granite suite was formed and/or emplaced during the D_2 phase. Continuing high-grade metamorphism, associated with this period of granitisation, is shown by extreme felspar and quartz-felspar blastesis marginal to areas of migmatised Kuiseb Formation, post-dating s_2.

4. The D_3 phase once again reflects the influence of compressive forces from the west, which gave rise to upright asymmetric, largely concentric, close folds. B_3 axial planes are believed to have been orientated near north-south and converged towards the north, possible due to the influence of relatively rigid basement rocks.

The recumbent Waldau Ridge antiform was deformed during this phase to give rise to the general pattern of the Waldau Ridge structure, corresponding to the Ramsay's(1967) Type 2 pattern of superimposition. The plunges of the Löwenberg antiform towards the north and the Ritter synform towards the south, reflect the original orientation of the lower and upper limbs of the recumbent Waldau Ridge antiform, respectively.

M_1 metamorphism continued throughout this phase and G2 granite was intruded as small stocks as well as large dykes and sheet-like bodies parallel to the axial plane of the Ritter synform. Larger amounts of this granite occur in the north-east of the area. Emplacement predates completion of the D_3 phase and the stock-like bodies are weakly foliated.

5. Evidence from the southern part of Gross Barmen shows that the rocks in this region do not reflect this earlier deformation. It is concluded that during this period, which the rocks of the Abbabis Swell and presumably the initial contents of the Khomas Trough, underwent three phases of deformation,

further sedimentation occurred in the Khomas Trough at shallower depths. These relatively younger members of the Kuiseb Formation are found south of the northern margin of the Okahandja Lineament and are characterised in part by the occurrence of spindle-shaped calc-granofels bodies.

6. Once again, northward-directed compressive forces caused deformation of these younger contents of the Khomas Trough, during the D_4 phase. Open folds in the Gross Barmen area die out north of the Okahandja Lineament, possibly due to the more competent nature of the rocks in this area as the result of earlier tectono-thermal activity.

The Okahandja Lineament as seen at present, developed during this phase as a zone of "flattening strain", in which the metamorphic banding cleavage developed possibly in part as a mylonitic banding essentially axial planar to D_4 folds in Zone II. The localisation of this zone in which greater strains were accommodated is believed to reflect the proximity of the relatively rigid mass of the Abbabis Swell as well as the fundamental weakness of the Okahandja Lineament.

Further vertical movements are believed to have occurred along the Okahandja Lineament during this period, so that the younger sediments were brought into the realm of amphibolite facies metamorphism (M_1) after the development of the metamorphic banding cleavage. Hence the growth of cordierite and sillimanite post-dating this foliation.

7. Continued compression was translated into large-scale strike-slip movements during the D_5 phase, with much of the movement having been concentrated along the northern margin of the Okahandja Lineament as shown by secondary features of this movement in the form of both brittle fracture and ductile shear strain phenomena. The orientation of the movement zone is essentially parallel to the orientation of the metamorphic banding cleavage.

The maximum P-T conditions in the area, at approximately 650°C and 400 to 450 MPa, were very close to those defining the boundary between brittle and ductile deformation, however, rock composition locally appears to have influenced the degree to which either type of deformation occurred. The M_1 metamorphism continued during this phase of deformation and slightly outlasted it as shown by unfoliated pegmatitic neosomes and the growth of sillimanite parallel to s_5. The G3, G4 and G5 granites were emplaced after the main tectonic events had ceased and are apparently related to the final peak of M_1 metamorphism, with fairly extensive migmatization of Etusis Formation rocks in the north of the Waldau Ridge structure.

8. The period of cooling down following on the major period of tectonothermal activity in this area was interrupted by a regional thermal event (M_2) superimposed on these rocks.

The Donkerhoek Granite was emplaced into the Okahandja Lineament during this thermal episode and is thought to be responsible for more widespread post-tectonic blastesis of lower grade minerals. Locally, the intrusion of the

Donkerhoek Granite is believed to have caused pseudomorphic recrystallisation of andulasite from sillimanite, as well as other local contact metamorphic effects.

9. Fairly extensive retrogressive effects which may in part be related to this lower grade event are evident in the area.

In summary then, the Damaran Orogeny, as reflected in the Waldau area, consisted of five major phases of deformation which took place during a single prolonged episode of amphibolite-facies metamorphism. Major orogenic movements gave rise to folds which trended parallel to the Damara Orogen (*sensu stricto*). Orogenic movements in the major trunk of the Pan-African Orogenic Belt, which roughly parallels the west coast of Africa, appear to have played an intermittent role in the area and influenced the tectonic evolution of the Waldau Ridge structure.

A few syntectonic granite bodies were emplaced at different times, together with a body of more basic rock. The Salem Granite in this area formed in large part through granitisation of Kuiseb Formation rocks. Further granite intrusions occurred in the early post-tectonic period together with extensive migmatisation of the Etusis Formation rocks and is related to the peak of metamorphism in the area. The later post-tectonic Donkerhoek Granite was emplaced into rather cooler country rocks and has a thermal aureole associated with it.

The Okahandja Lineament is recognised as a fundamental crustal weakness which strongly influenced the stratigraphic as well as the tectonic history of the area.

B. Relationship to a possible evolutionary model for the Damara Orogenic Belt

Discussion concerning the origin of the Damara Orogeny is clearly linked to that concerning the origin of the Pan-African orogenic belts as a whole. Most widely accepted views are that the Pan-African orogenic belts are the products of *in situ*, large-scale upwelling and remobilisation of sialic material along zones of weakness within cratonic blocks (Clifford, 1968; Shackleton, 1973) and in this respect the Damara Belt is regarded as being no exception (Martin, 1975).

In recent years, proponents of plate tectonics have attempted to apply the new global tectonics to the Pan-African and older orogenic belts (Burke and Dewey, 1970, 1973). Similarly, the Damara Belt has been re-examined for indications of a possible plate tectonic origin. In this particular case the mafic and ultramafic rocks which make up the Matchless Amphibolite Belt (Fig.2) have been proposed as representing the suture zone in a continental collision model (Hartnady, 1974). The zone of intense planar deformation surrounding this belt (Hälbich, 1970) possibly represents the deformation associated with a northward-dipping underthrusting zone (Hartnady, personal communication). In the subduction model, the central, plutonic zone - to a large extent the

Abbabis Swell - would represent the "magmatic arc" situated above a north-dipping subduction zone. Only the roots of this arc are seen at present.

In the view of the proponents of an "ensialic" or "*in situ*" upwelling origin for the Damara Belt, the central plutonic zone represents the mobilised and uplifted, eugeosynclinal portion of the geosyncline (Martin, 1965). The uplifted, southward-moving mass of this mobilised core was proposed by Hälbich (1970) to have provided the forces responsible for the intense planar deformation in the southern part of the Khomas Trough.

The present study has disclosed certain features which, although not directly supporting one or another hypothesis, are of importance in the understanding of tectonic relationships between the Abbabis Swell and the Khomas Trough.

The recognition of a major, primary, recumbent fold which verges towards the Khomas Trough (Waldau Ridge antiform) is believed to be the first recorded occurrence of such a feature along the south-east margin of the Abbabis Swell. Further to the south-west, major north-east trending folds are asymmetric with inclined axial planes and which similarly verge towards the Khomas Trough (Smith, 1965; Jacob, 1974). From this relationship, it seems possible that the Waldau area represents a higher structural level of the Abbabis Swell than that seen further south-west. Regional relationships in this zone certainly appear to indicate a large-scale fanning of the axial planes of macroscopic structures, outwards from the centre of the Abbabis Swell. This possibly indicates that there has been uplift and that movement outwards from this zone was initiated under the influence of gravity. In the classical descriptions of geosynclinal orogeny, such zones are termed "divergent", and are supposedly also characteristic in being the focus of orogenic, magmatic and metamorphic activity (Aubouin, 1965). It is important to note that in respect of the Damara Belt, there is apparently little bilateral symmetry about this zone, particularly in regards to orogenic events. The belt is markedly asymmetric and the zone of maximum deformation and mountain building is displaced some 80-100 km south of the "divergent" magmatic zone, to the vicinity of the Matchless Amphibolite Belt (Hartnady, in preparation).

The broad-scale structure of magmatic arcs is similarly reported to be characterised by vertical tectonics, which includes large-scale broad - to isoclinal - folds deformed and reactivated by the invasion of subjacent plutons (Ernst, 1974). The asymmetry of orogenic belts related to zones of plate convergence is well documented and characteristic.

The recognition of the nature of the Okahandja Lineament is considered to be the most significant feature to arise from this study. It was, however, only recognised at a late stage, with the result that much work still remains to be done in this connection. Conclusions regarding early vertical movements in this zone are made from indirect evidence as well as the proposals concerning vertical movements in the later stage of deformation (D_4). There is, however, more direct evidence to show that the Okahandja Lineament was the site of significant right-lateral strike-slip movement in late tectonic times (D_5).

Zones of intense strike-slip movement have been described as bounding zones of different tectonic character in more obviously ensialic orogenic zones such as the Limpopo Belt (Mason, 1973; Coward *et.al.*, 1973). It is also well documented that major zones of strike-slip movement play an important part in the accommodation of strains along coverging plate boundaries.

The northern margin of the Okahandja Lineament is recognised in this study as being the northern boundary of a significantly younger sedimentary basin which was not involved in the early major phases of deformation affecting the Abbabis Swell and presumably also the initial contents of the Khomas Trough. The total extent of this younger basin is not known, but it is believed possible that it underlies the entire area as far south as the Matchless Amphibolite Belt. This proposal is supported by the study of Porada (1973), who recognised the widespread occurrence of calc-granofels spindles (originally diagenetically formed marlstone concretions), as characterising a "lower" division of the sedimentary pile in the Khomas Trough. A less extensive, spindle-free portion is described by him as forming an upper division. The observations that similar spindles occur for a short distance south of the Matchless Amphibolite Belt may indicate that the southern margin of this younger basin became involved in the intense deformation which affected this southern zone.

It is stressed, therefore, that future studies of structural relationships between the Abbabis Swell and the Khomas Trough should not fail to take into recognition that early tectonic events in this region are not represented in the zone between the Matchless Amphibolite Belt and the northern margin of the Okahandja Lineament.

Wynne-Edwards (1976) proposed that the sialic crust responded differently to spreading forces in the asthenosphere throughout geologic time. This progressive change was related to a steady decrease in the ductility of the crust with decreasing temperature of the earth. In this respect it is perhaps significant that the Pan-African orogenic belts span the time of transition from the period of "subsolidus ductile flow" during the Proterozoic and the period of "brittle fracture and failure" during the Phanerozoic as proposed by Wynne-Edwards.

Kröner (in press) similarly proposed that "ensialic orogeny is caused by the same subcrustal forces which are operative during plate separation, ocean opening and continental collision", and that modern plate tectonic processes became increasingly common during the late Precambrian/early Paleozoic.

In the light of these proposals the possibility that certain structural and petrologic features in the southern part of the Khomas Trough are suggestive of the existence of a north-dipping zone of subduction in that area during the Late Precambrian, should not be regarded as general concurrence with the theories of the "new global tectonics".

Fig.30 shows how the major conclusions of this study might be related to such a model of subduction and continental collision.

Further work along the southern margin of the Abbabis Swell (Sawyer, in prep.) will hopefully provide further evidence as to the nature and evolution of the Okahandja Lineament. It is felt, however, that the area along the upper part of the Swakop River Valley between Okahandja and the Lievenberg Dome (Fig.2) will provide the greatest amount of information concerning the tectonic evolution of the Okahandja Lineament, as the Donkerhoek Granite intrudes only into a minor part of the zone in this area.

Fig.30. (see opposite page)
Schematic sections showing essential features of the proposed tectonic evolution of the area in relation to a possible subduction and continental collision site in the southern part of the Khomas Trough.

(a) D_2/M_1 Subduction. Gravity induced recumbent folds along southern margin of the Abbabis Swell. Uplift related to magmatic activity in this zone (magmatic arc) which is situated over a north-dipping subduction zone. Initial contents of the Khomas Trough deformed by isoclinal folding and by thrusting. Subduction zone migrates southwards in response to mass of tectonically accreted material. Younger sedimentary basin developes on the trench slope (fore-arc basin). Possible further vertical movement on vertical faults along the northern margin.

(b) D_4/M_1, D_5/M_1 Continental collision.Compression of contents of the fore-arc basin and development of zone of "flattening" along northern margin in response to buttressing effect of the Abbabis Swell (D_4). Accommodation of stresses in right-lateral movement along northern margin of the Okahandja Lineament, possibly with failure to subduct continental crust (D_5).

(c) M_2 Post-tectonic thermal event and intrusion of Donkerhoek Granite into the Okahandja Lineament.

MBC = Metamorphic banding cleavage;
MA = Matchless Amphibolite;
WR = Waldau Ridge;
GB = Gross Barmen hot springs.

(Line of section, shown in Fig. 2 is equivalent to that used by Hälbich (1970 - Plate XIV)).

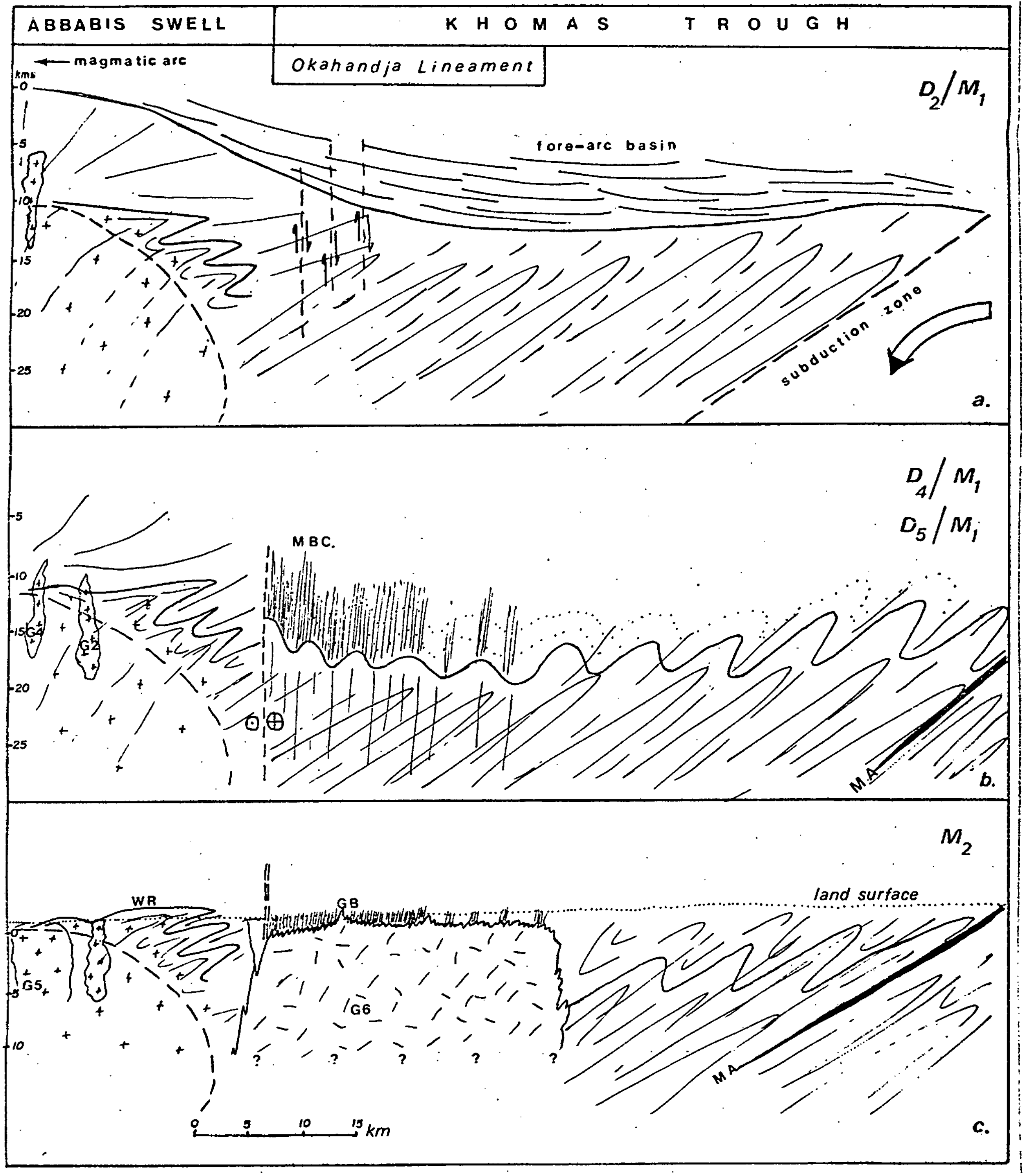

ABBABIS SWELL
KHOMAS TROUGH
magmatic arc
Okahandja Lineament
kms
0
5
10
15
20
25
D2/M1
fore-arc basin
subduction zone
a.
D4/M1
D5/M1
MBC.
G4
G2
MA
b.
M2
WR
GB
land surface
G5
G6
?
MA
0
5
10
15 km
c.

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Plate 1. Augen and ribbon-like, granular quartz segregations associated with narrow zones of boudinaged and deformed vein quartz segregations in zones of intense transposition and possibly by low-angle thrusting parallel to s_2(I.A.).(6I).

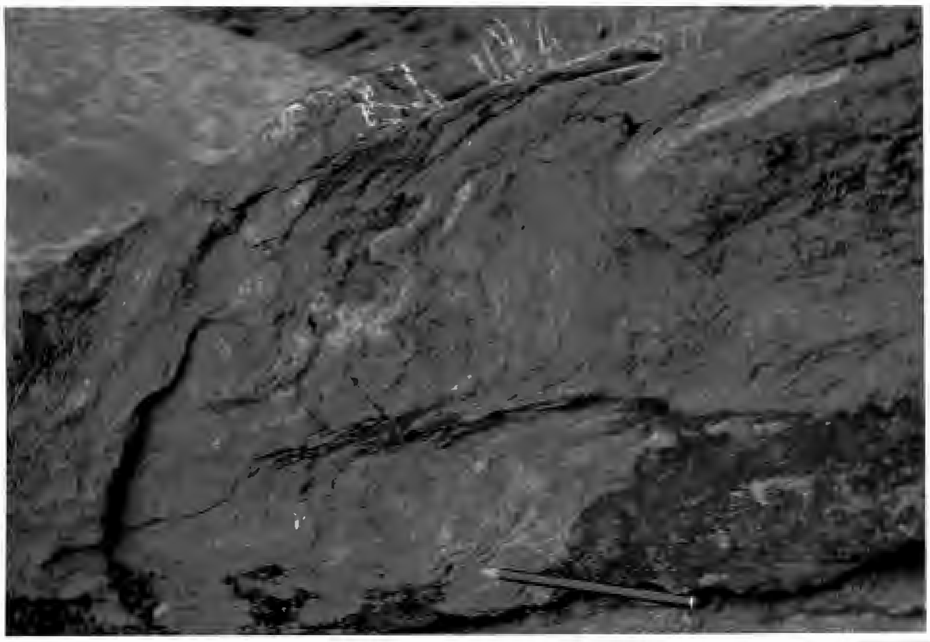


Plate 2. Drag-folds in thinly layered quartzite, schist sequence between zones such as depicted in Plate 1. (6J).

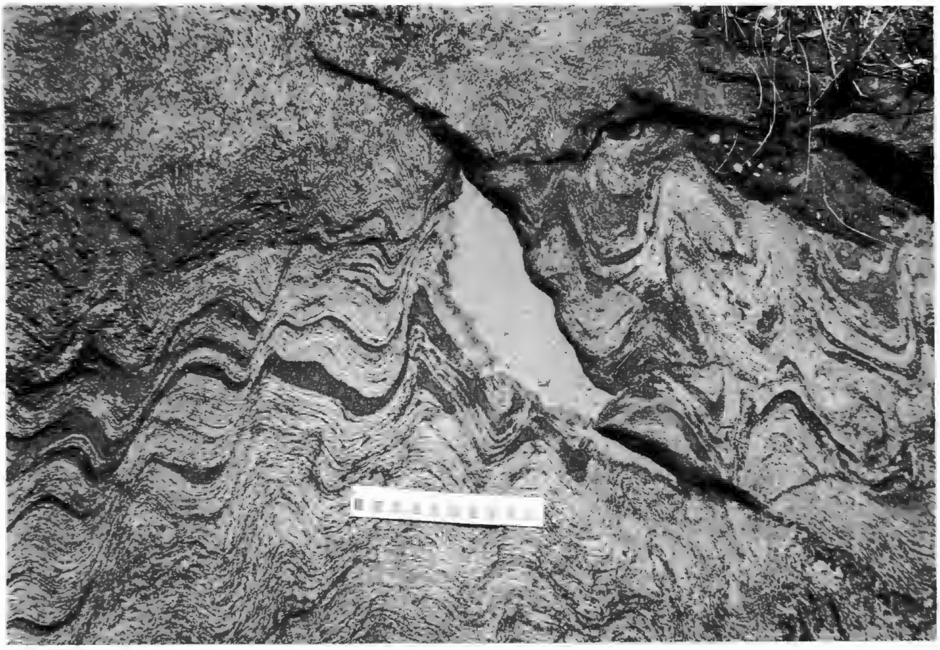


Plate 3. Minor shears in quartzo-felspathic gneiss (NsGn). Zones of maximum shear define the orientation of s_5 and may be occupied by slightly pegmatitic neosomes developed during the D_5. (Scale in cm) (4D).

Plate 4. D_4 phase folds. Very small concentric folds and open very big folds deform s_2. (8I).

Plate 5. Near horizontal compositional banding (s_0) (Zone II). Vertical metamorphic banding cleavage (s_1) (Zone II). Andalusite porphyroblasts show show strong preferred orientation parallel to s_2 (Zone II). Rounded porphyroblasts, probably cordierite, post-date s_1 and pre-date s_2, largely altered to white mica. (12I).

Plate 6. Selective development of metamorphic banding cleavage (s_1) (Zone II). Isolation of antiformal hinges, interpreted as possibly being due to "flattening" during development of s_1 (Zone II). (11I).

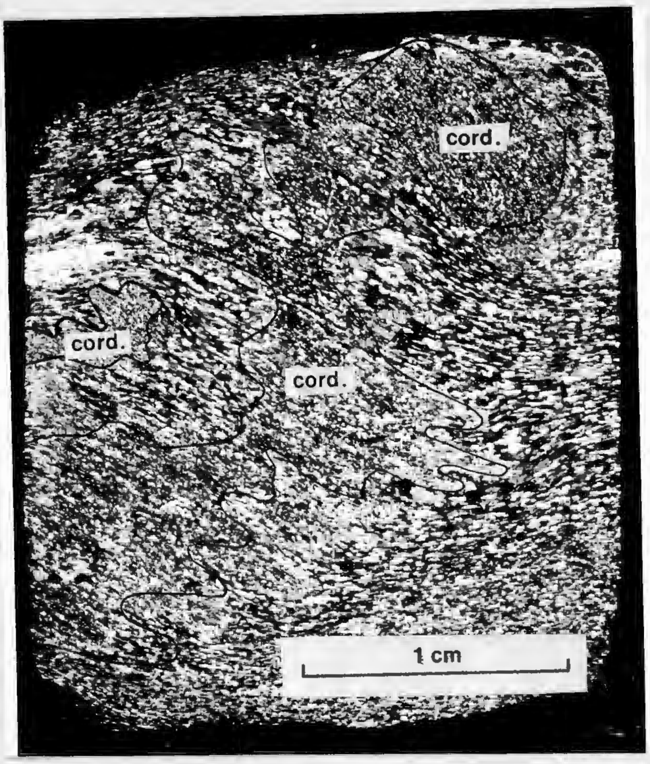


Plate 7.

Photomicrograph of rotated cordierite porphyroblasts. $s_i = s_e = s_1$ (Zone II), sharply deformed close to boundary of porphyroblast. Note flattened quartz fabric parallel to s_1 and development of coarser grained pressure shadow. (Crossed nicols) (9I).

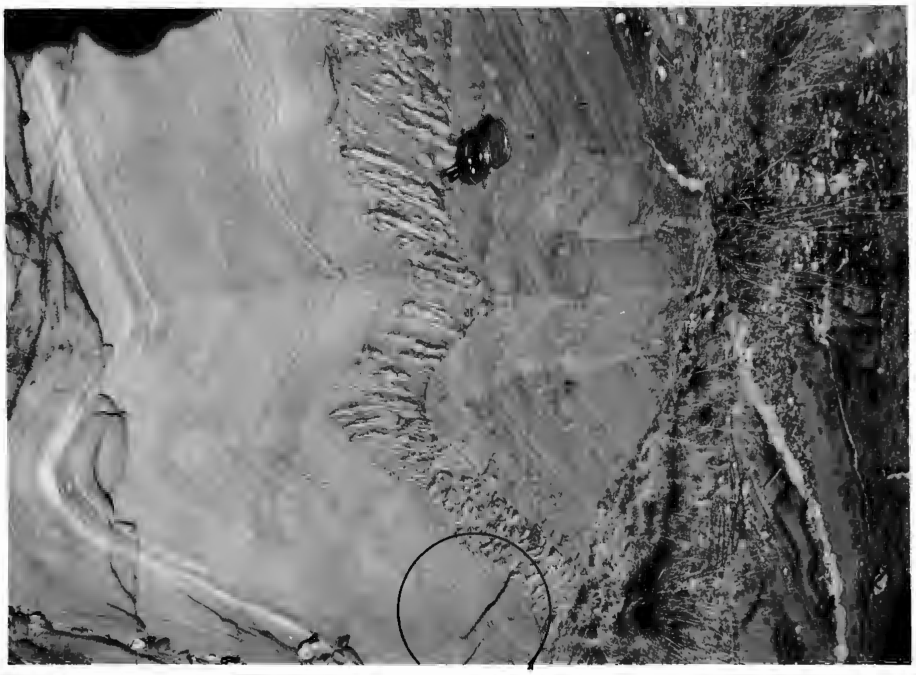
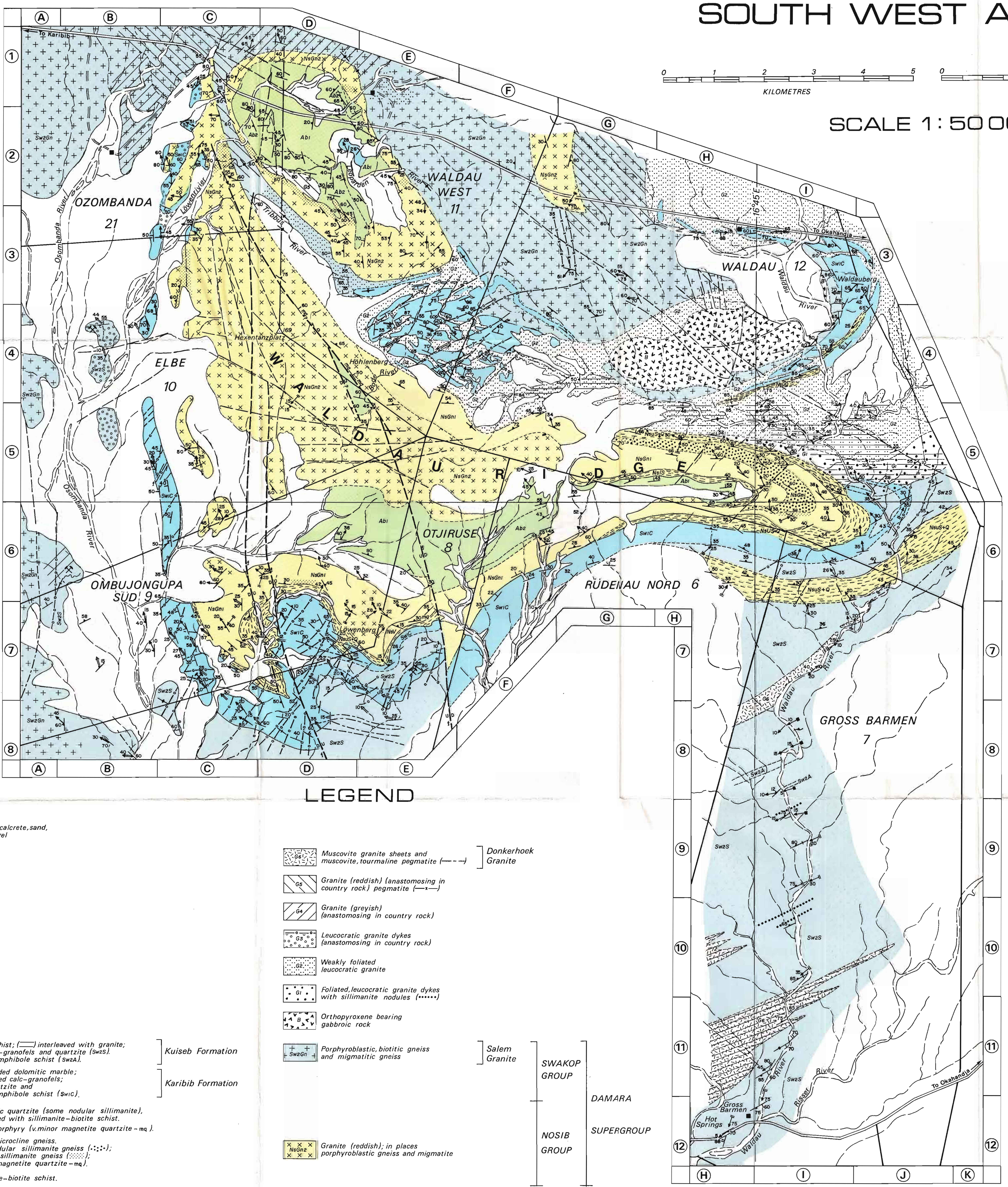
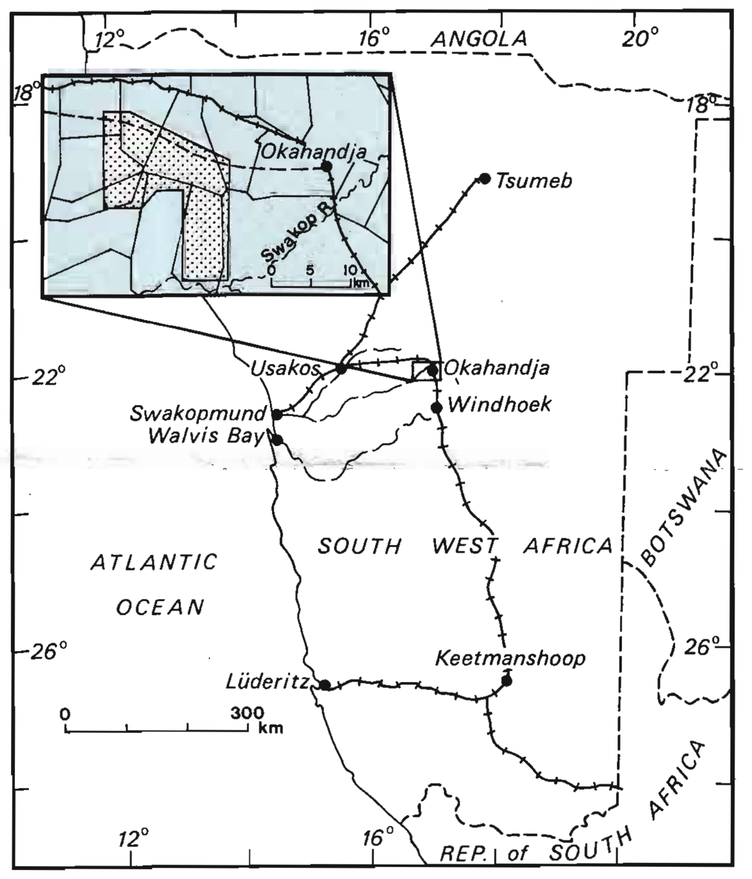


Plate 8. B_2 (II) folds developed as kinkband. Note sub-parallel growth of andalusite porphyroblasts and selective development of crenulation foliation parallel to axial plane. Circled, note slightly oblique s_1/s_0 (Zone II) relationship. (12I).

GEOLOGICAL MAP OF AN AREA WEST OF OKAHANDJA, SOUTH WEST AFRICA

SCALE 1 : 50 000





LOCALITY MAP

LEGEND

☐	Alluvium, calcrete, sand, scree, gravel			
Sw2A Sw2S	Biotite schist; (▭) interleaved with granite; thin calc-granofels and quartzite (Sw2S). Quartz-amphibole schist (Sw2A).	Kuiseb Formation	SWAKOP GROUP	DAMARA SUPERGROUP
SwIC	Thick banded dolomitic marble; thin banded calc-granofels; calc-quartzite and quartz-amphibole schist (SwIC).	Karibib Formation	SWAKOP GROUP	DAMARA SUPERGROUP
NsuS + Q	Feldspathic quartzite (some nodular sillimanite), interbedded with sillimanite-biotite schist.		NOSIB GROUP	DAMARA SUPERGROUP
NsV	Quartz-porphyry (v. minor magnetite quartzite – mq).		NOSIB GROUP	DAMARA SUPERGROUP
NsGnI	Biotite-microcline gneiss. Minor nodular sillimanite gneiss (·:;:·); iron-rich sillimanite gneiss (░); (v. minor magnetite quartzite – mq).		NOSIB GROUP	DAMARA SUPERGROUP
NsIS	Sillimanite-biotite schist.		NOSIB GROUP	DAMARA SUPERGROUP
Ab2	Marble; various metaquartzites; calc-silicate segregations; conglomerate.			ABBABIS COMPLEX
AbI	Leucocratic granitic gneiss; pegmatite and aplite; biotite schist and migmatite.			ABBABIS COMPLEX
G6	Muscovite granite sheets and muscovite, tourmaline pegmatite (— - - —)	Donkerhoek Granite		
G5	Granite (reddish) (anastomosing in country rock) pegmatite (—x—)			
G4	Granite (greyish) (anastomosing in country rock)			
G3	Leucocratic granite dykes (anastomosing in country rock)			
G2	Weakly foliated leucocratic granite			
GI	Foliated, leucocratic granite dykes with sillimanite nodules (••••••)			
B	Orthopyroxene bearing gabbroic rock			
Sw2Gn	Porphyroblastic, biotitic gneiss and migmatitic gneiss	Salem Granite	SWAKOP GROUP	DAMARA SUPERGROUP
NsGn2	Granite (reddish); in places porphyroblastic gneiss and migmatite		NOSIB GROUP	DAMARA SUPERGROUP

SYMBOLS

- Inclined, vertical compositional banding (bedding?)
- Inclined, vertical, undulating foliation
- Direction and plunge of mineral lineation
- Direction and plunge of minor folds
- Direction and plunge of minor folds and lineation
- Inclined, vertical crenulation foliation
- Inclined, vertical metamorphic banding cleavage
- Direction and plunge of minor folds
- Fault, relative upthrow (U) and downthrow (D) shown
- Wrench fault, relative direction of movement shown
- Fault, inferred
- Photolinear / fracture
- Lithologic boundary
- Lithologic boundary – inferred
- ⚒ Prospect
- △ Trigonometrical beacon
- Main road
- Secondary road
- Water course
- Farm boundary
- ■ Homestead
- Railway

PRU PC

Mapped and compiled by J.L. Blaine (1976); drawn by P.J. Eloff (1976); Chamber of Mines, Precambrian Research Unit, Geology Department, University of Cape Town. ©