South West Africa/Namibia
Suidwes-Afrika/Namibië

No. 6

South West Africa Series
Suidwes-Afrika Reeks

GEOLOGY OF A PORTION OF CENTRAL DAMARALAND, SOUTH WEST AFRICA/NAMIBIA

by

R. McG. Miller

Met 'n opsomming in Afrikaans onder die opskrif:

Geologie van 'n Deel van Sentraal-Damaraland, Suidwes-Afrika/Namibië

Republic of South Africa, Department of Mines
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(Explanation to Sheets 2014D and 2015C and portions of Sheets 2015A and 2015D)

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ABSTRACT

Mapping of this area, 6 500 km^2 in extent lying 70 km north-west of Omaruru, South West Africa, has revealed the following sequence of rocks, listed oldest to youngest: (I) gneiss of the Huab Complex; (2) the Damara Sequence comprising (a) Late Nosib to Early Swakop Naauwpoort Formation alkaline rhyolites, which are more than 6600 m thick and are characterised by very high K, high Ba, low Sr contents and an Rb deficiency (K/Rb=349), the extrusion of which was associated with block-faulting; it is suggested that the magma was generated by partial melting of chemically and mineralogically suitable deep crustal rocks, (b) Swakop Group of metasedimentary rocks consisting of 100 to 1 100 m of carbonate (Ugab Subgroup and Karibib Formation) overlain by almost 10000 m of schist (Kuiseb Formation), and (c) Mulden Group schist; (3) the porphyritic Salem Suite which has a border facies of diorite in the south-east; (4) the medium-grained Sorris-Sorris Granite, intrusive mainly into the Salem granite; (5) Karoo Sequence sedimentary rocks and sills and dykes of alkaline feldspar porphyry; (6) Karoo dolerite dykes and sills; (7) a previously undescribed intra- or post-Karoo stock of alkali granite and granite porphyry (Otjohorongo Granite) with associated ring dykes and cone sheets of quartz porphyry. The central granite stock is very highly differentiated (K/Rb=77) in relation to the outermost cone sheets (K/Rb=185); (8) the post-Karoo Okenyenya Complex; (9) the post-Karoo Kwaggaspan Carbonatite.

Rocks of the Naauwpoort Formation and the Swakop Group and their ultrametamorphic derivatives underlie most of the area and have thus been studied in considerable detail. Nomenclature has been revised and a purely lithostratigraphic terminology used. The evolution of the Nosib-Swakop eugeosyncline is discussed in the light of detailed stratigraphic and structural investigations. Under the influence of regional metamorphism which increased in grade towards the south, the Naauwpoort rhyolites became recrystallised, coarser grained and eventually remobilised. The resulting magma solidified to form the Sorris-Sorris Granite. Talc, tremolite, diopside, forsterite and monticellite appear successively in the Swakop carbonates, and Mg-rich chlorite, biotite, and locally cordierite, sillimanite and almandine in the schist. Post-tectonic intrusion of the Salem granite into low-grade regions produced a conspicuous thermal aureole. Zones of thermal metamorphism merge with those of regional metamorphism. Assemblages indicate pressures of between 4 and 5 kb in the south and 3,5 kb nearly 20 km farther north.

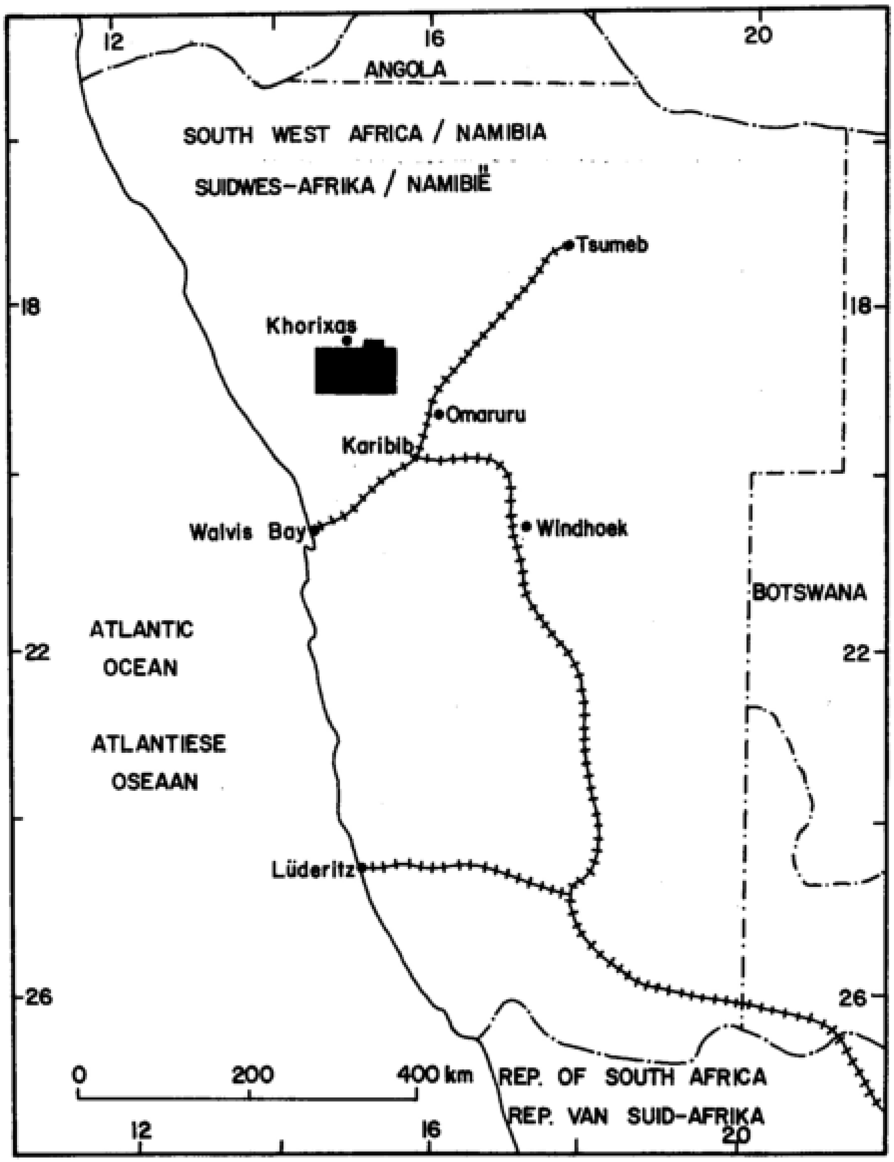


Fig. 1.1 — Locality map of area investigated.
Lokaliteitskaart van ondersoekgebied.

1. INTRODUCTION

1.1 LOCATION AND COMMUNICATIONS

The area is situated approximately 70 km northwest of Omaruru, South West Africa and was mapped during 1969-1970 (fig. 1.1). It covers approximately 6 500 km^2 and comprises geological sheets 2014D (Sorris-Sorris) and 2015C (Okenyenya), and small portions of sheets 2015A (Fransfontein) and 2015D (Epupa) (see folders 1 and 2).

The main access road, passing through the centre of the area, is that leading from Omaruru to Fransfontein. Farm roads, tracks and dry riverbeds serve the rest of the area.

1.2 PHYSIOGRAPHY

The topography is controlled to a great extent by the geology. The area can be roughly divided into a northern portion characterised by rolling hills of mica schist which in places give way to very mountainous terrain underlain by igneous rocks or marble (Summas Mountains; Mitten, Okotjize and Okongwe Folds*; Okenyenya Complex; Otjohorongo Granite) and a southern and western portion characterised by sand and gravel-covered flats which are underlain by the porphyritic Salem granite. In places these flats are broken by hilly outcrops of the medium-grained Sorris-Sorris Granite and metamorphosed Naauwpoort metavolcanics (Ais Dome) and by ridges of skarn, marble and quartz porphyry. The Otjongundu Plateau has an elevation of more than 400 m above the flats. Between the Mitten Fold and the Summas Mountains and north-west of the latter, flat monotonous expanses of calcrete occur. A fairly large area in the south-west is covered by stationary, grass-covered dunes.

The Ugab River has cut a deep south-westerly course through the centre of the area. Most of the other rivers, under the influence of this incision, flow more or less directly down to the Ugab. In the north-western corner of the area a minor watershed separates the Goantagab and Awahuab Rivers from the Ugab.

Fairly well-wooded bush country in the east is typified by *Colophospermilm mopane*, *Terminalia prunoides*, *Catophractes alexandri*, *Pachypodium lealii*, *Sterculia africana*, *Boscia albitrunca*, *Acacia montisustii*, *A. reficiens*, *A. giraffae*, and various species of *Commiphora*. In strong contrast, the vegetation of the extreme western edge of the area is limited to a few scant xerophilous shrubs of which *Acacia robyniana*, *Boscia albitrunca* and various species of *Commiphora*, *Petalidium* and *Euphorbia* are typical. In addition *Acacia albida* and *Combretum imberbe* occur in the sand-filled beds of the larger rivers. *Tamarix usneoides* grows where subsurface waters are brackish. A few small specimens of *Welwitschia mirabilis* occur in the extreme south-western corner of the area.

1.3 PREVIOUS WORK

The regional geology of the area as indicated on the Geological Map of South West Africa (1963), was gleaned mainly from unpublished maps and reports of the Bethlehem Exploration and Mining Corporation (1954) and from various reconnaissance surveys carried out by Martin (1965). Gevers and Frommurze (1929) briefly mention the red granite on Sorris-Sorris and discuss the Karoo sequence of the Otjongundu Plateau. The geology of portions of the eastern part of the area is outlined in a report by Cooke (1966). Mapping in the adjoining areas has been carried out by Gevers and Frommurze (1929), Clifford (1959, 1962, 1967), Frets (1969), Koornhof (1970), Guj (1970a), Hodgson (1972) and Klein (1978).

* The term "Fold" will be formally used for all interference structures.

2. GENERAL STRATIGRAPHY

A lithostratigraphic terminology has been used and recommendations of the International Subcommission on Stratigraphic Classification (1961) and the South African Committee for Stratigraphy (1971) have been applied.

The oldest rocks in the area are gneiss and quartzite of the Huab Complex which crop out in a small inlier just to the north of the Summas Mountains. A major unconformity separates these rocks from the overlying Damara Sequence (table 5.1). The base of the latter is the Naauwpoort Formation which is composed entirely of acid volcanic rocks. In the Summas Mountains welded pyroclastic rocks containing both block-size and ash-size fragments occur. Farther south in the Mitten Fold only ash flows have been observed. The metasedimentary rocks of the Swakop Group overlie the Naauwpoort volcanic rocks with a slight disconformity in places, but just to the north of the Summas Mountains volcanism and sedimentation overlap, resulting in a conformable interfingering succession.

The Ugab Subgroup, consisting mainly of dolomite with subordinate schist and minor quartzite and conglomerate, forms the base of the Swakop succession. Overlying these rocks are those of the Khomas Subgroup. These are made up of the thin but laterally extensive and exceedingly useful glacial marker, the Chuos Formation at the base, followed by the Kuiseb Formation. The latter, although mainly mica schist, contains a major dolomite near its base (the Karibib Formation) and several local quartzite and dolomite beds higher up.

The post-tectonic Salem Suite and Sorris-Sorris Granite were generated during post-Damara metamorphism*. The Sorris-Sorris Granite is considered the anatectic product of the Naauwpoort volcanics. The petrography, geochemistry and theoretical petrogenetic model of the rocks of the Salem Suite have been dealt with by Miller (1974).

The rocks of the Karoo Sequence overlie the Damara metasediments and post- Damara granites with a major unconformity. One small outcrop of Dwyka Formation rocks and one of Prince Albert Formation rocks occur near the Okotjize Anticline (not indicated on the map). By comparison the red, typically poorly sorted terrestrial deposits of the Omingonde Formation are more extensive. Southwest of Okenyenya these have been invaded by sills of feldspar porphyry and their associated feeder dykes. Dolorite dykes and sills of post-Omingonde age occur scattered through the area.

* As the succession of rocks which accumulated during the main volcanic and depositional episode has been called the Damara Sequence, subsequent events which affected these rocks, tectonism, metamorphism and plutonism are referred to as being post-Damara.

The Okenyenya Complex, described in detail by Simpson (1954), displays an intrusive relationship to the Karoo rocks. Another post-Karoo intrusive, the Otjohorongo Granite, occurs 17 km east of Okenyenya and is composed of a stock of alkali granite and granite porphyry with associated ring dykes and cone sheets of quartz porphyry. The Kwaggaspan Carbonatite is probably post-Karoo in age.

In figure 2. 1 the previous stratigraphic interpretation of the area (Geological Map of South West Africa 1963) is compared with that revealed by the present investigation. The most important changes are:

(1) The presence of Huab Complex gneiss just north of the Summas Mountains.

(2) Lavas in the Summas Mountains shown as Khoabendus in age are now considered to belong to the Naauwpoort Formation which falls within the Nosib Group.

(3) There are no Abbabis Formation rocks in the Mitten Fold nor is there any Nosib arkose - the whole pre-Swakop succession is composed of Naauwpoort pyroclastic rocks or their strongly recrystallised equivalents.

(4) The members and formations within the Swakop Group are differentiated.

(5) The Salem Suite and Sorris-Sorris Granite are distinguished.

(6) The Otjohorongo Granite and its associated dykes and sheets as well as the Naauwpoort metavolcanics of the Ais Dome form important additions to the map.

3. HUAB COMPLEX

3.1 GENERAL

The Huab Complex forms gently rolling hills in an area approximately 30 km^2 in extent immediately to the north of the Summas Mountains. Granitic gneiss is the main rock type. Subordinate highly sheared micaceous quartzite occurs within the gneiss on Renosterkop 389.

The gneiss is medium grained and adamellitic in composition (table 3.1) and displays a well-developed foliation that has a fairly consistent east-north-east trend. This foliation is enhanced in places by a marked segregation of quartz and feldspar into separate layers.

Table 3.1 APPROXIMATE COMPOSITIONS OF HUAB COMPLEX GNEISS AND QUARTZITE

Sample no.	Quartz	Potash feldspar	Plagioclase	Biotite	Muscovite	Accessory minerals
RM 914.......	30	30	38	2	—	zircon, ore
RM 915......	35	25	40	—	—	biotite, ore, zircon
RM 917.......	70	—	—	—	30	rutile, ore

RM 914, 915—gneiss.
RM 917—micaceous quartzite.

Thin sections of gneiss show the quartz to be highly strained. Grains are typically elongated and contacts between quartz grains are highly sutured. The potash feldspar is fresh microcline perthite. Strongly saussuritised plagioclase, of composition An_3 to An_5, has well-developed albite rims at contacts with potash feldspar. Biotite has a subparallel orientation within the foliation. All zircon grains observed were rounded to subrounded.

In the quartzite, quartz and long slender grains of muscovite respectively display striking granoblastic and lepidoblastic textures. The plain extinction of the quartz, together with the hexagonal outlines of most grains, indicate complete recrystallisation. This is in marked contrast with the strained quartz of the gneiss.

3.2 RELATIVE AGE OF THE GNEISS

The medium-grained strongly foliated nature of the gneiss contrasts markedly with the very coarse porphyritic to porphyroblastic texture of the rocks of the Fransfontein Suite of the Kamanjab Inlier 50 km to the north (Clifford, Rooke and Allsopp 1969). However, the age of 1700 - 1800 Ma (Burger, Clifford and Miller 1976) is the same as that for the Fransfontein granite. This concordance of ages suggests that the intense deformation of the Huab Complex (F_2-Frets 1969) occurred at very high temperatures and that the Huab gneisses formed during this tectonothermal event. Intrusion of the Fransfontein granite was late- to post-tectonic. Gradational contacts between gneiss and granite (Frets 1969) suggest intrusion into very hot country rocks.

4. NAAUWPOORT FORMATION

The name “Noupoort Series” was proposed by Martin (1961) for a succession of pre-Swakop acid and intermediate volcanic and sedimentary rocks which occurs on the farm Naauwpoort 511 in Damaraland. Frets (1969, p. 47) gives reasons for preferring the name “Naauwpoort Formation”. The term has also been adopted for the area under discussion because the vast quantities of acid pyroclastic rocks underlying the metasedimentary rocks of the Swakop Group in the Ais Dome, Mitten Fold and Summas Mountains (fig. 2. 1) are considered to be equivalent to the Naauwpoort Formation in its type area. Other small outcrops of Naauwpoort rocks occur just north of the Summas Mountains and on Rooipoort 414 (fig. 2.1).

4.1 STRATIGRAPHY

In the area covered by this report the Naauwpoort Formation is composed exclusively of volcanic rocks; sedimentary rocks such as those occurring west of Khorixas (Welwitschia-Frets 1969) are entirely absent. Most of the succession (Lower Naauwpoort) is immediately pre-Swakop in age, but the final extrusions (Upper Naauwpoort) are actually interbedded with the basal Swakop sediments.

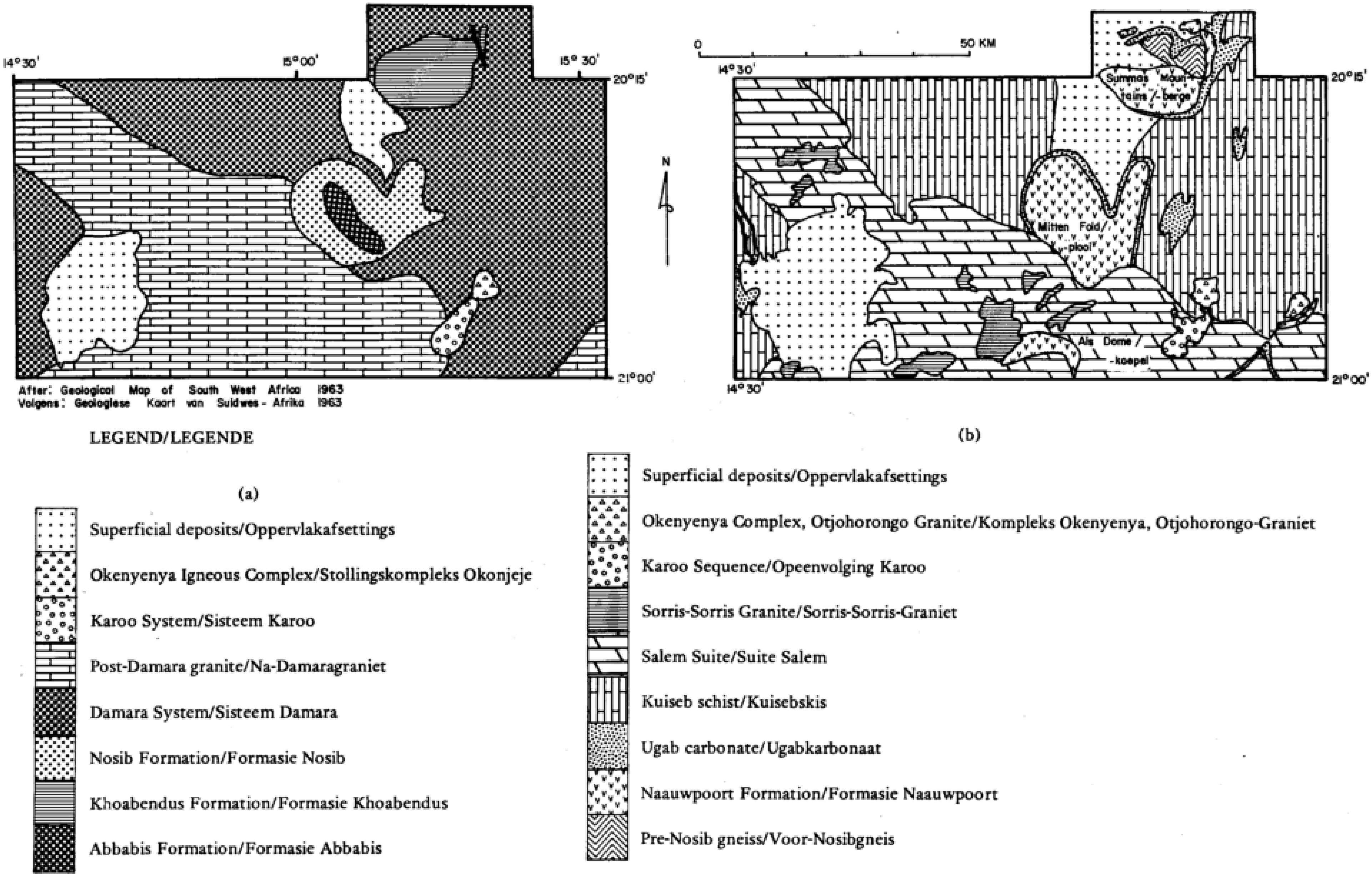


Fig. 2.1 – Comparison of the geology of the area as shown by (a) the Geological Map of South West Africa (1963), (b) the present investigation.
Vergelyking van die geologie van die gebied soos getoon deur (a) die Geologiese Kaart van Suidwes-Afrika (1963), (b) die huidige ondersoek.

Only the Lower Naauwpoort will be considered in detail here as the Upper Naauwpoort and its stratigraphic significance, as well as the correlatives of the whole Naauwpoort Formation, have already been discussed by Miller (1974).

4.1.1 Lower Naauwpoort Formation

The Lower Naauwpoort rocks occur in the Ais Dome, Mitten Fold and Summas Mountains, where they underlie the Swakop metasedimentary rocks either conformably or with only a slight discordance. As the base of the succession is not exposed, its thickness exceeds the maximum value of 6600 m measured in the Summas Mountains. The volume of volcanic rocks between the Ais Dome and the Summas Mountains probably exceeds 7 000 km^3.

The two sections recorded in table 4. 1 are both taken from the Summas Mountains, as similar sections from the Mitten Fold provide only very limited information. In the latter locality recrystallisation induced by metamorphism has produced rocks with a monotonous arkose-like appearance and uniform light reddish-buff colour; all that can be seen of the original primary features is the relict pyroclastic texture and then only on weathered surfaces. In the whole structure the only place where the Naauwpoort volcanic rocks retain their original colour and felsitic igneous appearance is on Karstenville 405.

The lowest horizon exposed is a massive purplish agglomerate made up mainly of angular roughly equidimensional lapilli (fine ash - ¼ mm, ash - ¾ to 4 mm, lapilli - 4 to 32 mm, blocks > 32 mm, after Wentworth and Williams 1932) set in a matrix of ash (comprehensive reviews of pyroclastic rocks, their recognition and origin are given by Smith 1960; Ross and Smith 1961; Cooke 1966 and Von Brunn 1969). This is followed by a thick grey porphyritic lava. The remainder of the succession consists almost entirely of pyroclastic flows. Most of the flows contain variable amounts of ash and lapilli (figs 4.2 and 4.4) but there are a few composed only of ash and very fine ash (table 4,1), while others contain blocks (and bombs?) that can exceed 1 m in diameter (figs 4.3 and 4.5). Flows with slightly porphyritic lithic fragments occur intermittently throughout the succession. There are two thin friable tuffs, one above the porphyritic lava on Renosterkop 389 (table 4.1) and the other 480 m below the Swakop sedimentary rocks near the northern boundary fence of Macaria 390. In the Mitten Fold 5 km north-west of Otjiwapeke village two thin interbedded amphibolites are exposed in the gorge cut by the Otjongundu River.

Regionally the lava and coarse pyroclastic rocks are limited to the Summas Mountains. The Mitten Fold is made up entirely of ash flows. Recrystallisation induced by post-Damara metamorphism has, completely destroyed the original textural features of the Ais Dome rocks but it is probable that these were also ash flows.

4.1.2 Upper Naauwpoort Formation

The Upper Naauwpoort Formation rests uncomfortably on the Lower Naauwpoort rocks and consists of a sequence of rhyolitic pyroclastic rocks (fig. 4.6) and acid to intermediate lavas which interfinger with the basal units of the Swakop Group. The penultimate flow is a bostonite which directly underlies the glaciogenic Chuos Formation. The final pyroclastic deposit is interbedded with the metasedimentary rocks of the Chuos Formation and contains "dropped in" inclusions [figs 4.7 (a) and (b)]. A detailed description of the sequence is given by Miller (1974).

4.2 PETROGRAPHY

4.2.1 Lower Naauwpoort Formation

Apart from the two massive friable tuffs mentioned in table 4.1, the Lower Naauwpoort pyroclastic rocks are extremely hard, well compacted, partially to completely welded and have a typical felsitic appearance. They are dominantly grey or red in colour, but buff, pink, brown and black units occur, the last especially in the northern and eastern parts of the Summas Mountains. In the ash flows, which are usually poorly sorted, ash and fine ash predominate over angular and irregularly shaped lapilli and blocks of pyroclastic material and felsitic (fig. 4.5), vesicular (fig. 4.2) and flow-banded lava. Larger blocks are usually somewhat rounded (figs 4.3 and 4. 5) while most elongated inclusions are orientated parallel to bedding or flow banding (figs 4.2 and 4.4). A few flows are made up entirely of ash.

Most of the ash flows can be classified either as normal ignimbrites (fig. 4.5) or as eutaxitic ignimbrites (fig. 4.4). Some of the normal ignimbrites, largely confined to the Summas Mountains, have undergone such extreme welding that the pyroclastic texture has been all but destroyed. Fiamme are rather common in some specimens. The eutaxitic ignimbrites, which predominate in the Mitten Fold, have a flow-banded appearance produced by long narrow discontinuous slightly sinuous streaks. Although Ross and Smith (1961) maintain that the foliated structure of eutaxitic ignimbrites is due to compaction, it would appear that in the case of some of the Naauwpoort rocks a slight segregation of coarser and finer material has taken place as a result of flow (fig. 4.4). The foliation is enhanced by the parallel arrangement of elongated fragments.

A peculiar feature of most of the ash flows, even the strongly recrystallised material in the southern portion of the Mitten Fold (fig. 4.8), is that the fresh surfaces generally do not show the pyroclastic texture. This only becomes apparent on weathered surfaces.

Thin sections do not reveal a great deal about the original texture of these rocks, as outlines of individual fragments can be observed very rarely. Outlines of typical glass shards are entirely lacking. This can be ascribed partly to welding (Smith 1960, p. 824; Cook 1966, p. 165) but is mainly due to strong devitrification. Four main features can be recognised: (1) Irregular cryptocrystalline patches that usually grade into (2) coarser grained patches, also irregular in shape, in which grains can reach 0,1 mm in diameter. The coarser- and finer-grained portions almost certainly represent the original fragments and matrix of the rock. (3) Many sections show axiolitic streaks and bands made up of much coarser-grained quartz and feldspar. These are often quite distinct in hand specimen. (4) Devitrification spherulites are present in most samples and can be extremely abundant (fig. 4.9). In addition there are rare finely crystalline radiating growths of quartz and feldspar which suggest further crystallisation after spherulites had formed. In a few specimens phenocrysts and inclusions are surrounded by a whorled or fluidal-textured groundmass.

Table 4.1 TWO SECTIONS THROUGH THE LOWER NAAUWPOORT FORMATION IN THE SUMMAS MOUNTAINS

Traverse in a south-south-easterly direction from point C on section line ABCD (sheet 2015C)		Traverse in a north-easterly direction from point C on section line ABCD (sheets 2015A and C)	
Lithology	*Thickness in metres*	*Lithology*	*Thickness in metres*
Contact with Damara not exposed	—		
Reddish-buff finely vesicular felsitic ash flow with a few fine lapilli	140		
Brown fragmented feldspar porphyry, and red felsite with 3-m-thick layer of lithophysae (fig. 4.1)	35	Conformable contact with Upper Naauwpoort	—
Red and reddish-buff felsitic ash flow. Layers with many lapilli and others with lithophysae. Massive to flow banded (fig. 4.2)	335		
Greenish-grey agglomerate with ash matrix and large lava blocks (fig. 4.3)	35	Black intensely welded ash flows and pyroclastic flows. Small porphyritic blocks in the upper portions with feldspar phenocrysts up to 6 mm	420
	(545)		
Greyish-brown flow-banded slightly vesicular ash flow with abundant lapilli. A few lithophysae. Concentration of lapilli variable. Relatively thin black agglomerate 65 m from base of this unit	290	Light-brown ash flow with numerous lapilli and blocks	100
Grey and brown feldspar porphyry, fragmented in places. Average length of phenocrysts 2 mm	60	Brown feldspar porphyry	100
Grey flow-banded felsite, slightly agglomeratic	290		
Grey ash flow with numerous lapilli and small blocks. Irregular patches with many small lithophysae	45		
Brown flow-banded felsitic lava	20		
Grey felsite	60		
	(415)		
Brown slightly vesicular very fine-grained ash flow. Lapilli rarely present	140	Light-brown ash flow	210
Grey fine ash flow, banded in upper portion	355	Grey flow made up entirely of fine ash	305
Grey ash flow with layer of coarse agglomerate in the middle	80		
Grey very vesicular ash flow	65		
Several grey well-laminated ash flows containing a few lapilli. Some layers contain fragments of feldspar porphyry. A thin layer of lithophysae in the middle	610	Several grey and black ash flows with lapilli in places. A few thin flow-banded fine ash flows	730
Grey indistinctly laminated slightly vesicular felsite, slightly porphyritic	145		
	(900)		
Fine purplish-grey indistinctly laminated ash flow	425	Fine grey felsitic ash flow, laminated in places	170
Dark reddish-brown ash flow with numerous elongated lapilli and fragments up to 15 cm long and 3 cm wide aligned within the sinuous banding. Three thin separate flows at the base	90	Black pyroclastic flow composed of ash, lapilli and blocks	85
Grey slightly vesicular ash flow	20	Buff-coloured ash flow containing small buff-coloured blocks	80
Dark brownish-red quartz-feldspar porphyry, average diameter of phenocrysts 2 mm	15	Fine grey felsitic ash flow, lapilli at top, flow banded in places	90
Light-grey quartz-feldspar porphyry which is agglomeratic in the lowermost 8 m	190	Dark-grey pyroclastic flow, ash matrix, pink and buff-coloured lapilli and blocks	10
Grey ash flow containing abundant lapilli and blocks in places	155	Grey felsitic ash flow	80
Light-grey agglomeratic quartz porphyry. Contains fragments of white felsite. Phenocrysts rounded and up to 2 mm in diameter	240	Grey pyroclastic flow. Ash matrix, buff-coloured lapilli and blocks	40
Grey ash flow with numerous elongated lapilli and small blocks	215	Grey felsitic ash flow, flow laminations	270
	(925)	Grey friable tuff	10
			(665)

TABLE 4 (*continued*)

Traverse in a south-south-easterly direction from point C on section line ABCD (sheet 2015C)		Traverse in a north-easterly direction from point C on section line ABCD (sheets 2015A and C)	
Lithology	*Thickness in metres*	*Lithology*	*Thickness in metres*
Grey quartz-feldspar porphyry lava becoming reddish towards the base. Base agglomeratic. Phenocrysts up to 2 mm in diameter	415	Grey quartz-feldspar porphyry lava, agglomeratic in the lower 10 m. Contains a few isolated lapilli	405
Grey feldspar porphyry lava as above	470		
	(835)		
Dark purplish agglomerate, breccia	+845	Dark purplish agglomerate, breccia; fragments seldom larger than 3 cm across	+850
Total thickness of lava	835	Total thickness of lava	405
Total thickness of pyroclastic rocks	4 900	Total thickness of pyroclastic rocks	3 550
Total thickness of all volcanic rocks	5 735	Total thickness of all volcanic rocks	3 955

Fig. 4.1—Flow-banded ash flow containing a large proportion of ash, fairly numerous lapilli and a few small blocks. Elongated inclusions are parallel to flow-banding. Certain bands appear to be composed almost entirely of ash. Western margin, Mitten Fold.
Vloeigestreepte asvloei wat 'n hoë persentasie as, taamlik baie lapilli en 'n paar klein blokke bevat. Langwerpige insluitsels lê parallel met die vloeigestreeptheid. Sekere lae lyk asof dit ampter geheel en al uit as bestaan. Westelike rand, Mittenplooi.

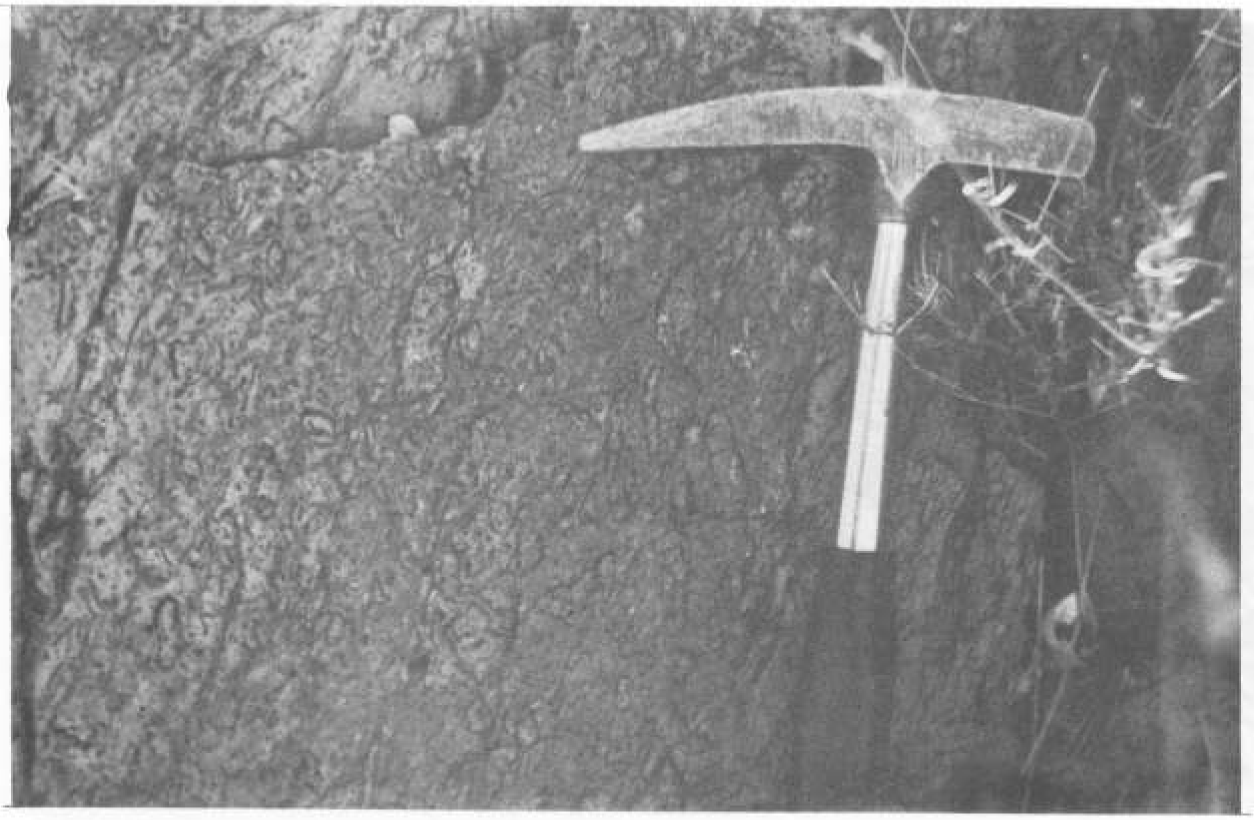


Fig. 4.2—Ash flow containing abundant angular lapilli and small blocks of vesicular lava. Elongated inclusions have a parallel orientation. Southern edge of the Summas Mountains.
Asvloei wat volop hoekige lapilli en klein blokke van blasiesrige lawa bevat. Langwerpige insluitsels het 'n parallelle oriëntasie. Suidelike rand van die Summasberge.

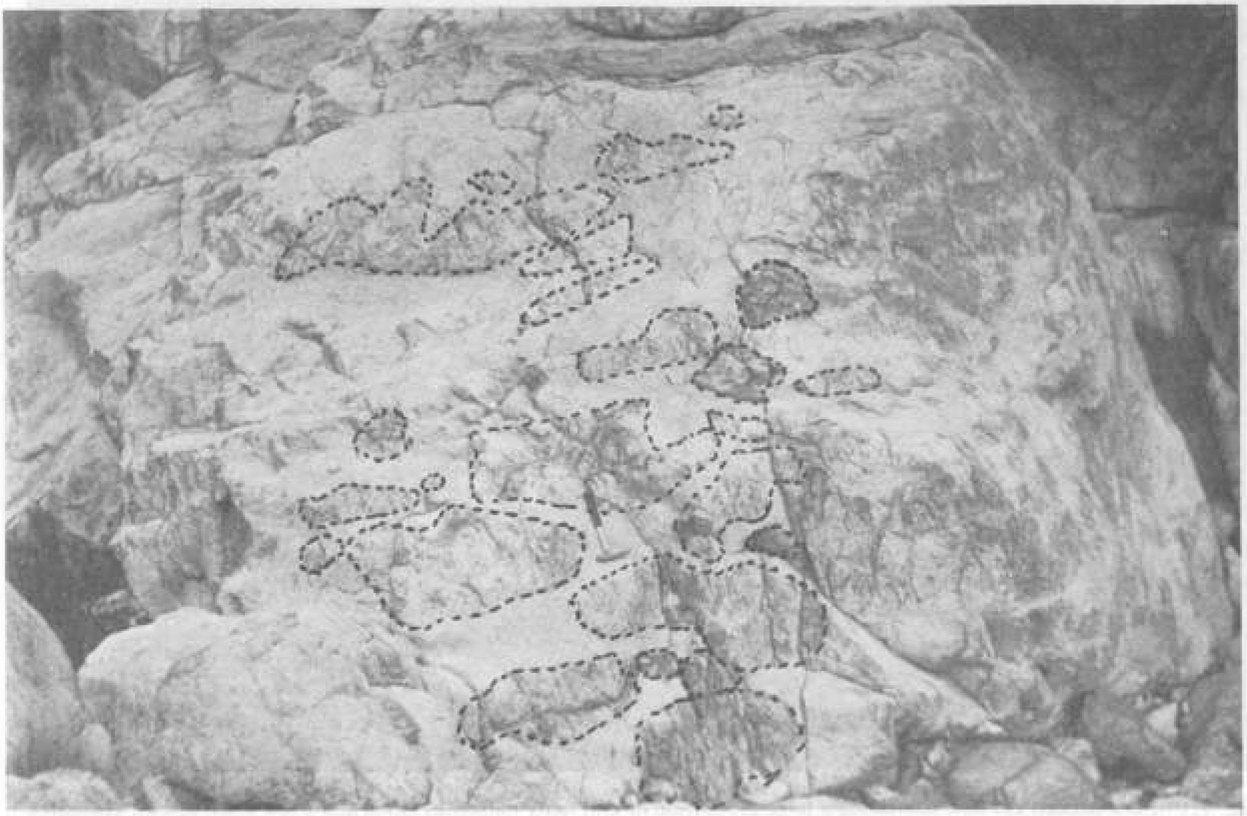


Fig. 4.3—Pyroclastic flow made up of ash and large blocks (bombs?) of felsitic lava. Some of the blocks exceed 1 m in length Southern portion of the Summas Mountains.
Piroklasvloei wat uit as en groot blokke (bomme?) van felsitiese lawa bestaan. Sommige van die blokke is meer as 1 m lank. Suidelike deel van die Summasberge.

Fig. 4.4—Pyroclastic flow made up of ash, lapilli and rounded blocks (bombs?) of red felsitic lava. Eastern portion of the Summas Mountains.
Piroklasvloei wat uit as, lapilli en afgeronde blokke (bomme?) van rooi felsitiese lawa bestaan. Oostelike deel van die Summasberge.

Fig. 4.5—Vesicular ash flow containing numerous compressed lithophysae. Southern portion of the Summas Mountains.
Blasiesrige asvloei wat baie saamgedrukte litofises bevat. Suidelike deel van die Summasberge.

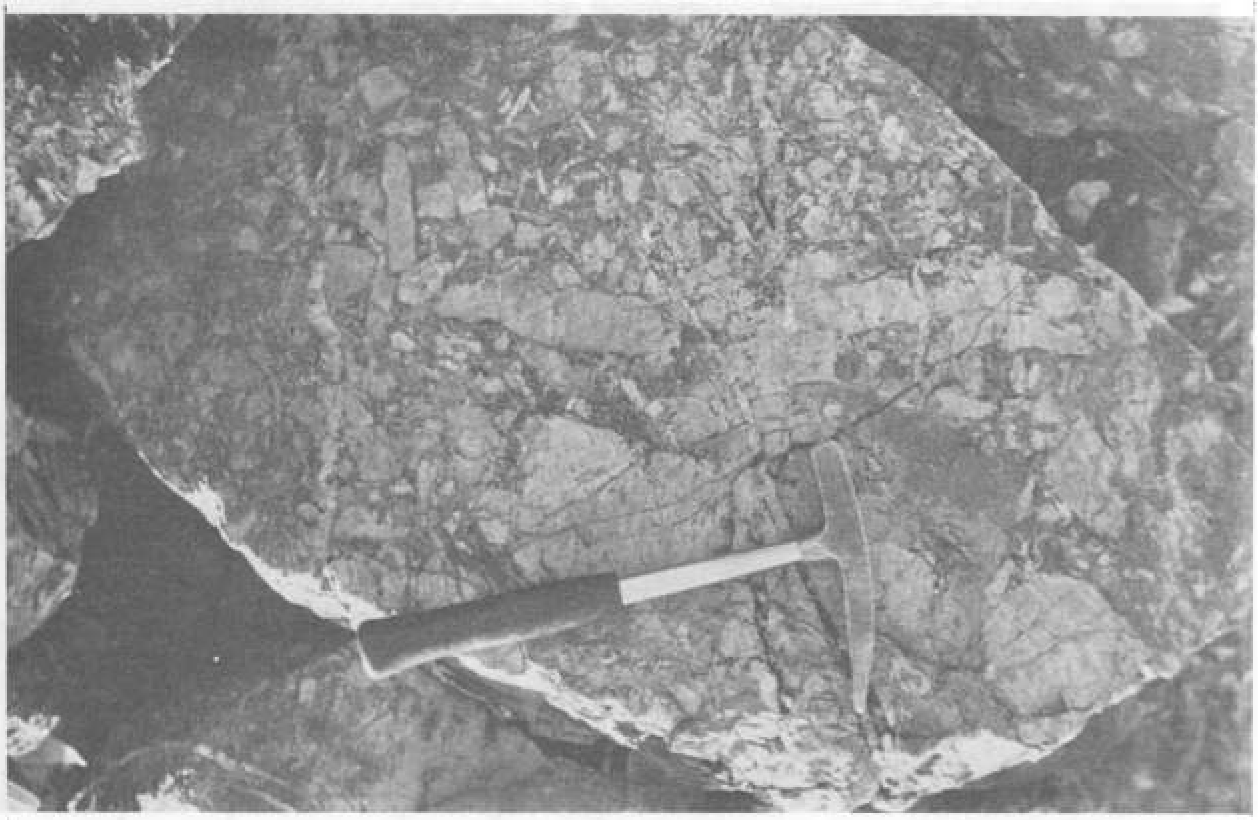


Fig. 4.6—Unsorted angular pyroclastic fragments supported by a matrix of sedimentary carbonate. Zone 4, Upper Naauwpoort Formation, south-eastern portion of Minorca 71.
Ongesorteerde hoekige piroklastiese fragmente in 'n matriks van sedimentêre karbonaat. Sone 4, Formasie Bo-Naauwpoort, suidoostelike deel van Minorca 71.

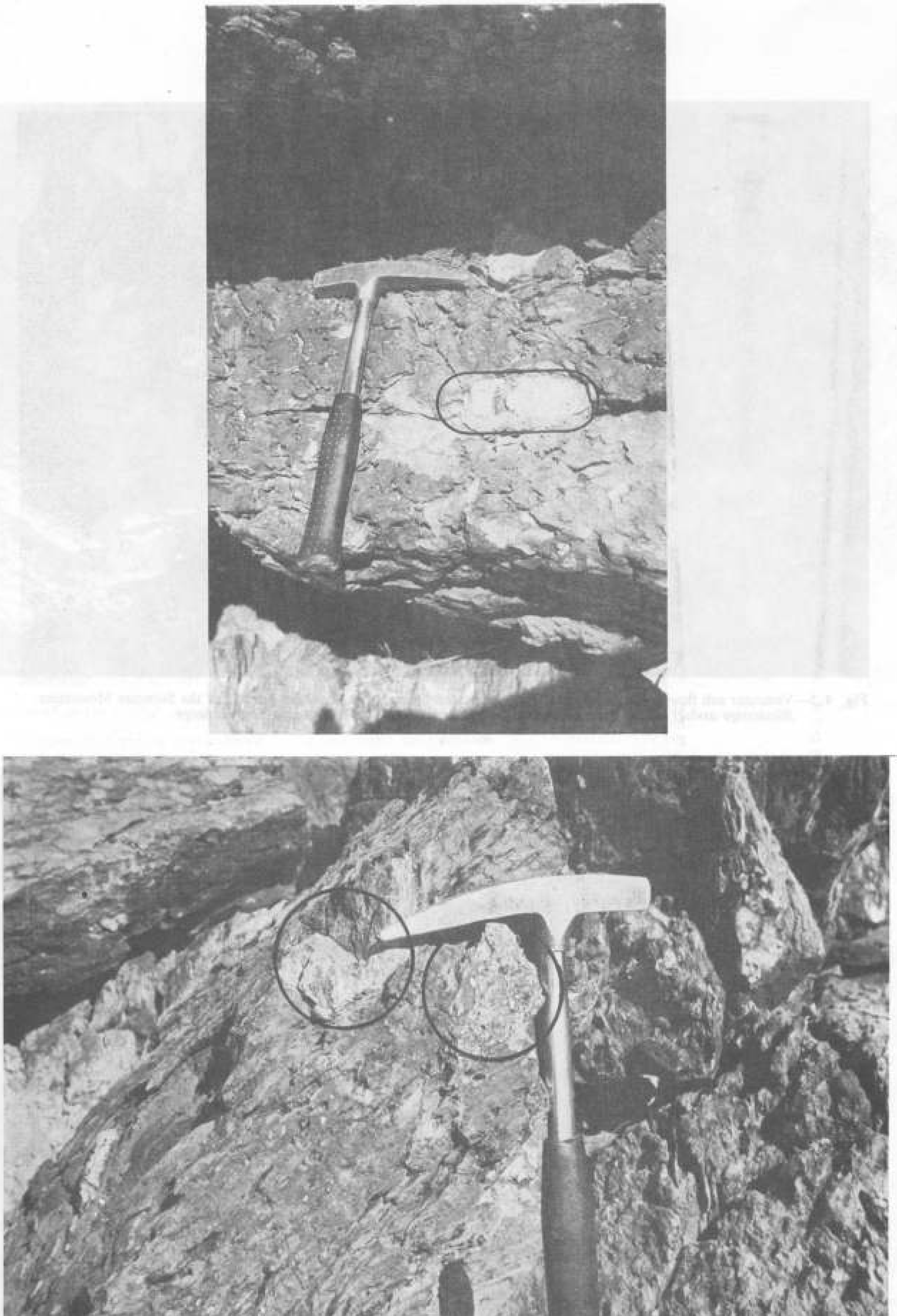


Fig. 4.7 (a) and/en (b)—Knobbly, vesicular, fine-grained pyroclastic deposit within the Chuos Formation, zone 8, Upper Naauwpoort Formation. Both photographs show ice-rafted granite inclusions (ringed). Central portion of Löwenfontein 84. *Knobbelrige, blasiesrige fynkorrelrige piroklasafsetting in die Formasie Chuos, sone 8, Formasie Bo-Naauwpoort. Albei foto's toon ysvervoerde granietinsluitsels (gekring). Sentrale deel van Löwenfontein 84.*

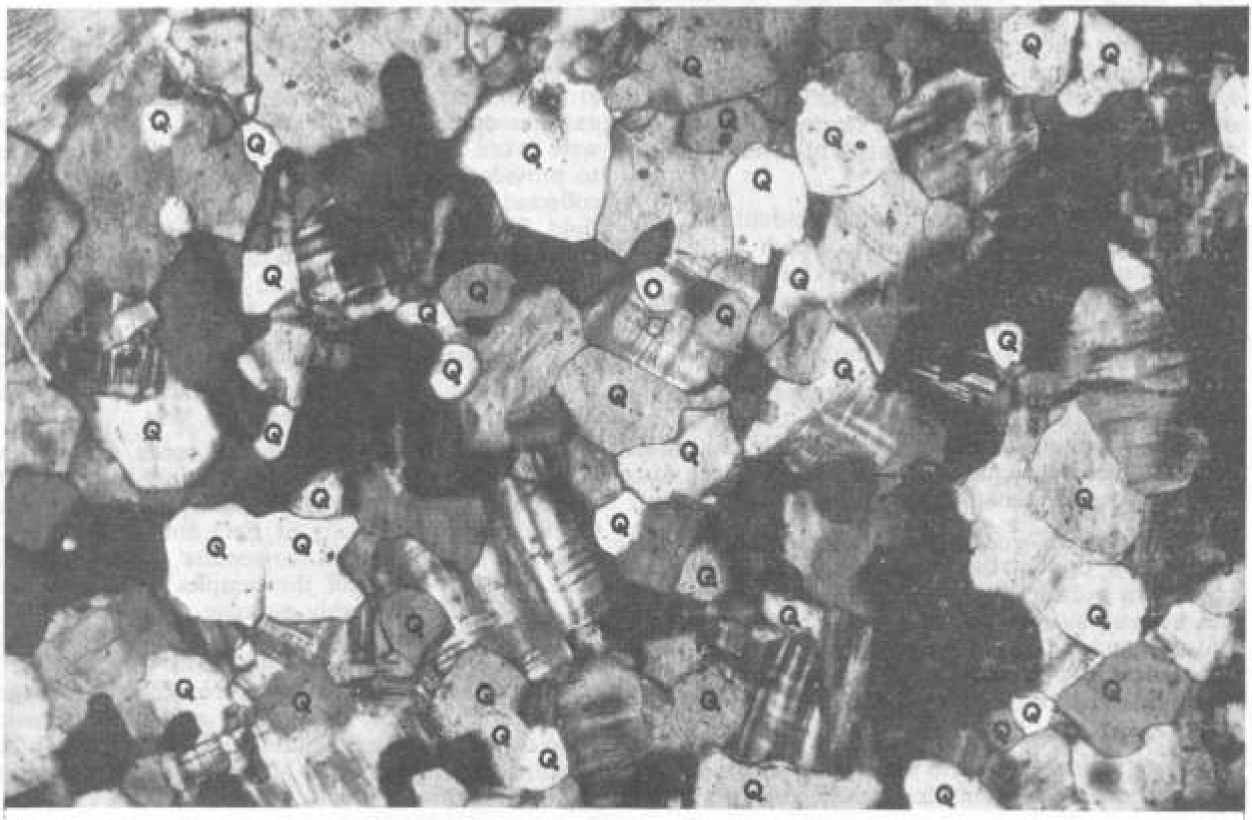


Fig. 4.8—Photomicrograph of strongly recrystallised Naauwpoort rhyolite showing abundant microcline. Quartz grains have been marked Q. Southern portion of Mitten Fold (×50).
Mikrofoto van sterk geherkristalliseerde Naauwpoortrioliet met volop mikroklien. Kwartskorrels is met 'n Q gemerk. Suidelike deel van die Mittenplooi (×50).

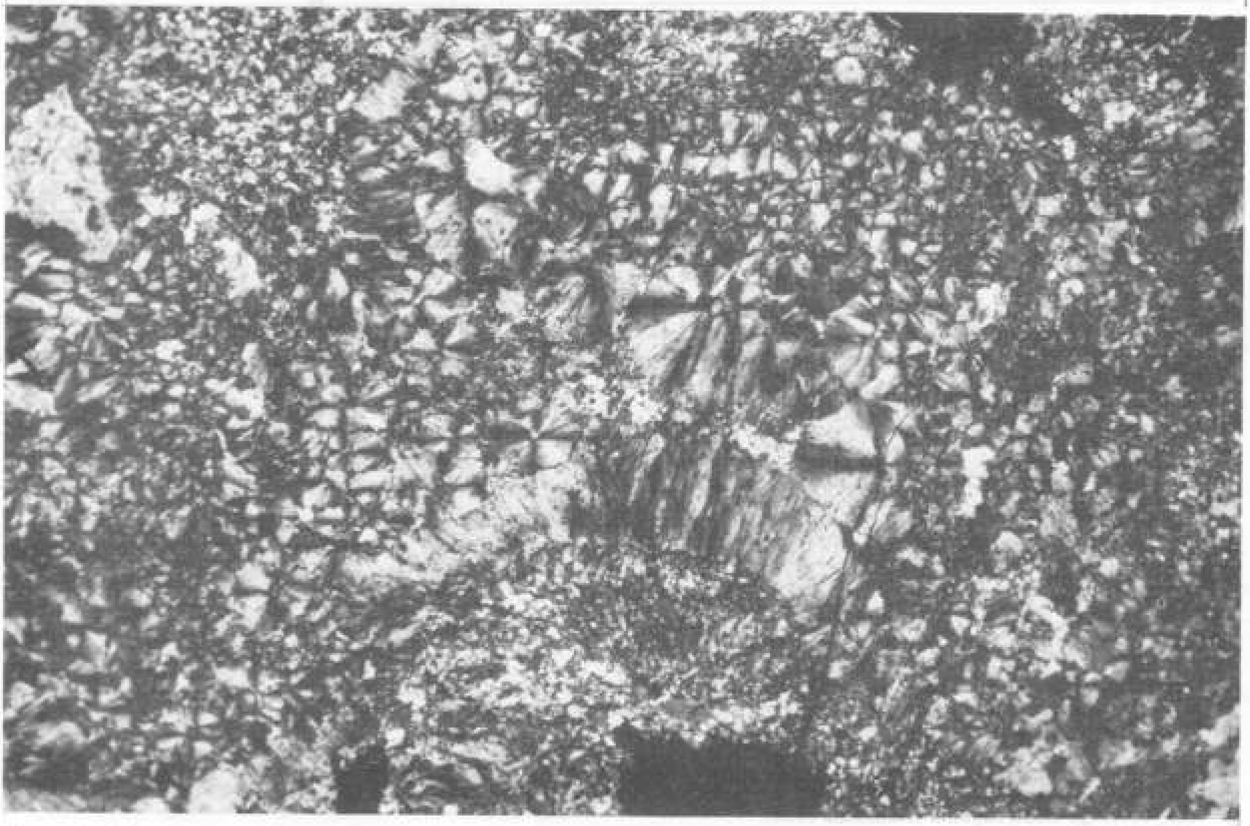


Fig. 4.9—Photomicrograph showing spherulites in devitrified Naauwpoort ash flow (×20).
Mikrofoto wat sferoliete in gedevitrifiseerde Naauwpoortasvloei toon (×20).

The amount of ore varies considerably. Light-coloured specimens contain very little, but abundant very fine-grained ore granules are disseminated through some of the darker rocks. In other samples thin streaks and irregular patches of oxidised ore are present. Small octahedral phenocrysts of ore also occur. Devitrification has effected a redistribution of ore granules resulting in the formation of stellate concentrations of ore in the centres of several spherulites.

Certain specimens contain small amounts of very fine-grained muscovite or biotite which is usually confined to definite portions of rock, either axiolitic streaks or zones between individual fragments. Muscovite-filled fractures at one locality indicate a post-consolidation origin for the mica.

Sections of lithophysae show a radiating structure of microcrystalline needles. Cryptocrystalline to fine-grained quartzo-feldspathic material fills the voids between these structures and in many places also forms a core to the structure.

Phenocrysts of quartz and feldspar make up less than 15 per cent of the porphyries. Feldspar phenocrysts are euhedral or subhedral, slightly clouded and have an average size of 2 mm. Untwinned alkali feldspar and albite with chess-board twinning predominate. Only one specimen contains albite phenocrysts (An_{0-4}) with normal albite and Carlsbad twins.

Quartz phenocrysts have undergone partial resorption and are either subhedral, rounded or embayed. Most of them have a very undulose extinction and broken phenocrysts are fairly common in the pyroclastic rocks.

4.3 GEOCHEMISTRY

Analyses of five samples of Naauwpoort rocks are presented in table 4.2 and cation percentages and mesonorms in table 4.2 (a). Three samples were taken in the Summas Mountains and, in order to provide a regional spread, two samples were also collected near the western margin of the Mitten Fold. Sample RM 778 is from the porphyry lava near the base of the succession in the Summas Mountains. Three samples were collected very near the top of the Lower Naauwpoort on Karstenville 405 (RM 475, RM 477) and Macaria 390 (RM 482). The fifth sample (RM 913) is from the porphyritic bostonite lava of the Upper Naauwpoort which underlies the Chuos Formation on Renosterkop 389.

The four Lower Naauwpoort rocks are typical alkali rhyolites and compare reasonably well with Nockolds's (1954) average alkali rhyolite and, but for the relative amounts of FeO and Fe_2O_3, Na_2O and K_2O, with certain comendite glasses (Noble 1968, p. 169). Three of the samples (RM 778, RM 477, RM 482) are highly potassic. Sample RM 475 has quite normal contents of Na and K. Samples RM 475, RM 477 and RM 482 have very low CaO contents when compared with Nockolds's average. The Late Palaeozoic to Tertiary acid igneous rocks of West Africa (Black and Girod 1970) are similar in that they have very low Mg and Ca contents and a slightly alkaline character.

Table 4.2 CHEMICAL ANALYSES AND INTER-ELEMENT RATIOS OF WHOLE-ROCK SAMPLES FROM THE NAAUWPOORT FORMATION

Sample no.	RM 778	RM 475	RM 477	RM 482	RM 913	(a)
SiO_2	74,14	75,31	73,59	74,41	61,91	74,57
TiO_2	0,11	0,23	0,20	0,11	1,33	0,17
Al_2O_3	10,19	12,27	12,37	11,79	14,38	12,58
Fe_2O_3	1,54	0,00	1,08	1,07	2,24	1,30
FeO	0,43	0,62	0,86	0,60	3,00	1,02
MnO	0,09	0,04	0,04	0,04	0,13	0,05
MgO	0,08	0,23	0,17	0,00	1,11	0,11
CaO	0,62	0,09	0,05	0,11	1,89	0,61
Na_2O	0,61	3,56	2,35	1,02	4,02	4,13
K_2O	8,09	5,23	7,35	9,30	5,42	4,73
P_2O_5	0,00	0,00	0,00	0,00	0,31	0,07
l.o.i.*	1,18	1,17	0,68	0,65	2,53	0,66†
H_2O^-	0,11	0,02	0,01	0,07	0,00	—
Totals	97,19	98,77	98,75	99,17	98,27	—
Trace elements, ppm						
Rb	222	133	201	167	137	—
Ba	2 002	925	900	194	1 037	—
Sr	31	17	19	8	71	—
Inter-element ratios						
(Na+K)/Al	1,33	1,08	1,20	1,36	0,98	1,05
K/Na	14,60	1,65	3,50	10,20	1,55	1,28
K/Rb	303,00	327,00	304,00	462,00	328,00	—
K/Ba	34,00	47,00	67,00	398,00	45,00	—
Ba/Rb	9,00	7,00	4,50	1,20	7,60	—
$K/Sr \times 10^{-2}$	2,60	3,10	3,80	11,60	0,80	—
Ba/Sr	65,00	55,00	47,00	24,00	15,00	—

RM 778—Porphyry lava near base of succession (table 4.1). Central Summas Mountains.
RM 475—Ash flow, top of succession, Karstenville 405.
RM 477—Ash flow, top of succession, Karstenville 405.
RM 482—Ash flow, top of succession, Macaria 390.
RM 913—Bostonite, zone 7, Upper Naauwpoort succession, northern portion Renosterkop 389.
(a)—Average alkali rhyolite (Nockolds 1954).
*—Loss on ignition.
†—H_2O^+.
Analyst: R. McG. Miller.

Table 4.2 (a) CATION PERCENTAGES AND MESONORMS OF ANALYSED NAAUWPOORT FORMATION ROCKS

Sample no.	RM 778	RM 475	RM 477	RM 482	RM 913
Cation percentage					
Si	74,06	72,06	70,67	71,76	60,21
Ti	0,09	0,17	0,15	0,08	0,98
Al	12,01	13,85	14,01	13,41	16,49
Fe^{3+}	1,16	0,00	0,79	0,78	1,64
Fe^{2+}	0,36	0,50	0,70	0,49	2,45
Mn	0,08	0,04	0,04	0,04	0,11
Mg	0,12	0,33	0,25	0,00	1,61
Ca	0,67	0,10	0,06	0,12	1,97
Na	1,19	6,61	4,38	1,91	7,59
K	10,31	6,39	9,01	11,45	6,73
P	0,00	0,00	0,00	0,00	0,26
Mesonorm					
Quartz	38,50	33,00	30,50	31,60	15,20
Orthoclase	51,60	29,70	43,60	57,00	27,00
Albite	5,90	33,00	21,90	9,50	37,90
Anorthite	1,30	—	—	0,10	2,90
Muscovite	—	1,80	1,20	—	2,20
Biotite	—	2,10	1,30	0,30	8,90
Actinolite	—	—	—	0,10	—
Diopside	0,80	—	—	—	—
Wollastonite	0,30	—	—	—	—
Sphene	0,30	0,30	0,20	0,20	2,90
Ilmenite	—	0,20	0,20	—	—
Magnetite	1,10	—	1,20	1,20	2,50
Hematite	0,40	—	—	—	—
Apatite	—	—	—	—	0,70
Ratio					
Ab/An	4,50	0, ∞	0, ∞	95,00	13,00

A comparison of the compositions of alkali rhyolites with the average alkali granite given by Nockolds (1954) reveals small but significant differences which, by and large, hold for the analyses of the Naauwpoort rocks. The Al_2O_3 content of alkali rhyolites is slightly lower than that of the alkali granite, indicating a slightly more alkaline character. Total Fe contents are more or less the same but Fe_2O_3 exceeds FeO in the volcanic rocks (see also Rooke 1970, on Aden rhyolites). This can probably be ascribed to oxidation of FeO during subaerial flow. Sample RM 475 which has a light-buff colour and no ferric iron, is therefore somewhat anomalous.

All the analyses have low totals which are not improved very much by the trace-element contents. Values for loss on ignition were checked by carrying out repeat determinations. It is probable that a large proportion of the shortfall can be ascribed to Cl, F and possibly S in view of the fact that peralkaline acid glasses are characterised by a high Cl content (Nicholls and Carmichael 1969, p. 287). If this suggestion were correct, then it is significant that the total for lava (RM 778) is lowest of all, because gaseous material would not nave been able to escape from the lava as readily as from the vesicular pyroclastic rocks.

Analyses for the trace elements Rb, Ba and Sr were made because of their strong association with certain major elements and because they are very sensitive indicators of differentiation. Rb^+ (1,47 Å) shows a close association with K^+ (1,33Å). Electro-negativities and ionisation potentials are very similar. Under conditions of extreme fractionation the slight size difference becomes important and leads to a concentration of Rb during differentiation, resulting in a decreasing K/Rb ratio (Taylor 1965). Generally Rb enters K positions in micas in preference to those in feldspar. Ba^{2+} (1,34Å) is very similar in size to K^+ (1,33Å) and this is the only major element that Ba^{2+} substitutes for. Ba^{2+} is captured in early formed K-minerals but, due to a slightly covalent character of the Ba - O bond, small amounts remain until a very late stage and can even become enriched at the end of a differentiation cycle. Because of the contrasting behaviour of Rb and Ba (early removal of Ba from the liquid and gradual concentration of Rb), the Ba/Rb ratio decreases with differentiation and is a very sensitive indicator (Taylor 1965). Potash feldspar contains about twice as much Ba as co-existing biotite.

The behaviour of Sr^{2+} (1, 18Å) is complex. It is intermediate in size between K^+ (1,33Å) and Ca^{2+} (0,99Å). It prefers eight- or ten-fold co-ordination with oxygen and thus does not enter pyroxene or biotite to any marked extent. Sr substitutes for Ca in plagioclase, apatite and sphene and for K in potash feldspar. Sr increases during fractionation and the Ca/Sr ratio decreases (Taylor 1965). Sr competes with Ba for lattice sites in feldspar but due to the more ionic nature of the Ba - O bond, Ba is preferentially accepted into early formed minerals and the Ba/Sr ratio in feldspar decreases with fractionation.

The trace-element results are characterised by low Sr, very variable but generally high Ba and, as indicated by the high K/Rb ratios, low Rb concentrations. The Naauwpoort rocks of the Khorixas area of Damaraland also have rather high K/Rb ratios (Frets 1969, p. 85). Comparisons with analyses of pitchstones (Carmichael and McDonald 1961), differentiated rhyolites (Siedner 1965) and peralkaline glasses (Nicholls and Carmichael 1969) show comparable trace-element distributions but they do reveal that the Ba content is rather high in the Naauwpoort rocks. Only the early volcanics and the Paresis Complex (Siedner 1965) have similar values (2210 ppm Ba). Barium is depleted in all peralkaline rocks. The K/Rb ratios of the Naauwpoort rocks are distinctly higher than those of the Scottish pitchstones (Carmichael and McDonald 1961) and the early Paresis volcanics and higher than the 150 to 300-ppm range of "normal" K/Rb ratios (Taylor 1965, p. 144).

A comparison of the trace-element concentrations in the sample taken near the base of the succession (RM 778) with those taken higher up (RM 475, RM 477, RM 482) indicates a decrease in Ba and Sr contents, Ba/Rb and Ba/Sr ratios and an increase in K/Ba and K/Sr ratios towards the top. The K/Rb ratios are variable but indicate no significant change in the amount of Rb (see next section).

The biotitic bostonite (RM 913) from the Upper Naauwpoort has a composition that corresponds very closely to Nockolds's (1954) average alkali trachyte and to Daly's (1933) average bostonite. Major differences are slightly lower contents of Al_2O_3, MgO and total alkalis in the sample. The excess of FeO over Fe_2O_3 can probably be ascribed to the presence of the biotite. The low total may again be due to non-analysis of Cl, F and S.

Trace-element concentrations and ratios are very similar to the Lower Naauwpoort rocks. The only exception is Sr, which is higher and consequently the K/Sr and Ba/Sr ratios are lower.

These analyses show a broad correspondence with those reported by Frets (1969, p. 57) of samples taken from the type area west of Khorixas where alkali rhyolite is succeeded by subvolcanic nordmarkite, bostonite and foyaite. The main difference is that Frets's rocks are soda-rich. They also contain more CaO, MgO, and Fe in the form of Fe_2O_3. The trace-element concentrations are similar.

4.4 PETROGENESIS

4.4. 1 Origin of the succession

The sections accompanying the geological mars of the Summas Mountains area show a fault contact between the northerly dipping Naauwpoort Formation and the gneiss of the Huab Complex. This contact coincides with the present course of the Löwenfontein River. Although it is almost entirely obscured by Ugab and Mulden sedimentary rocks and Tertiary to Quaternary deposits, there is considerable indirect evidence which strongly suggests that the Summas Fault is pre-Naauwpoort in age: (1) Rocks of the Lower Naauwpoort succession do not overlie the gneiss. The almost conformable transition between the Naauwpoort and Ugab rocks gives no indication of a long period of highly effective erosion such as would be required to remove 6600 m of welded pyroclastic rocks. (2) The Naauwpoort rocks are not turned up against the fault. (3) The interfingering Upper Naauwpoort and Lower Ugab successions overlie the Lower Naauwpoort rocks conformably and the latter succession actually straddles the Summas Fault. (4) Along the subsidiary faults just to the north, the breccia zones in the Upper Naauwpoort rocks never exceed 1,50 m in width whereas in the adjoining gneiss the breccia zones are never less than 6 m wide and are more commonly between 15 and 20 m wide. (5) The latter are thoroughly cemented by drab-coloured chert-like material that was probably deposited by volcanic hydrothermal and gaseous solutions which used the porous breccia zones as access channels.

The Summas Fault is one consequence of the movements in the crust which accompanied the development of the Damara geosyncline. The author believes that magma generation was directly related to block-faulting and sinking of the crustal segment to the south and that the rising magma used the fault plane as a feeder channel (fig. 4. 10). Eruptions from the volcanoes situated near the fault (note the limitation of lavas and coarse pyroclastic rocks to the Summas Mountains), although producing vast quantities of pyroclastic material, were not accompanied by violent explosive activity. Near-surface ash flows, unable to move very far north because of the upfaulted block, spread mainly southwards. In the north these lapped against the edge of the fault scarp partly obscuring its original nature. Clastic wedges probably formed at the foot of the fault scarp (not exposed on surface). Periodic fault movements which accompanied volcanism only ceased after the first Hakos sediments had been deposited. Only when the down-faulted depression had been completely filled (the Lower Naauwpoort succession exceeds 6 600 m in thickness) were the volcanic deposits able to spread over the upfaulted gneiss. By this time deposition of the Ugab Subgroup sediments had already begun. The Naauwpoort rocks were subsequently folded against the gneiss during the post-Damara F_1 phase of folding.

The thick sequence of volcanic rocks extending southwards from the Summas Mountains had a significant influence on the later depositional and tectonic history in the area. Thinning of the Swakop metasedimentary rocks over the Naauwpoort sequence suggests that the latter formed a ridge, the Naauwpoort Ridge, which extended into the geosyncline at an angle of almost 90° to its margin. The Naauwpoort Ridge is now represented by the Summas Mountains, Mitten Fold and Ais Dome (fig. 2.1).

4.4.2 Origin of the magma

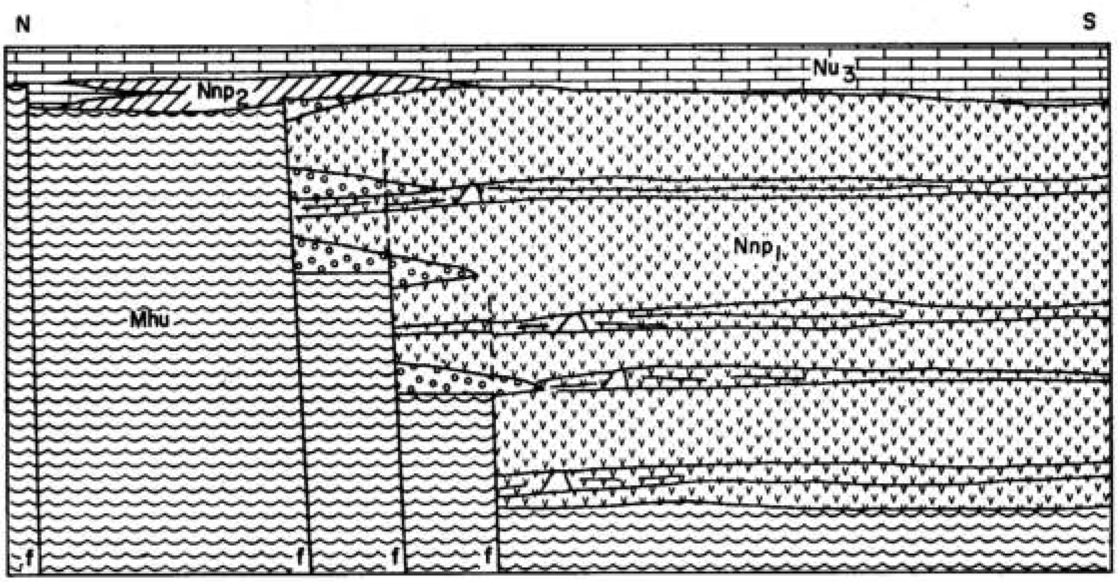
The Naauwpoort rocks are no exception to the general limitation of alkaline rocks and large-volume deposits of acid pyroclastic rocks to cratonic areas where they are associated either with rifting and block sinking or zones of instability (Smith 1960; Barth 1962; Bailey 1964; Le Bas 1971). Magma production by means of complete or partial melting of acidic crustal rocks (Bailey and Schairer 1964; Siedner 1965 and Bailey 1974b) satisfactorily accounts for the large volume, alkaline character and trace-element peculiarities of the Naauwpoort rocks.

Partial melting of a parent rock approximating in composition to granodiorite could produce an alkaline magma quite readily. Most of the Ca would remain in the residue and if the main Ca host were plagioclase, then a large proportion of Al would also be retained by this mineral. The associated melt would tend to be Al deficient. An analogy can be found in the results of experiments carried out by Winkler and Von Platen (1960) and Green (1966, 1969) in which partial melting of calcite-bearing illitic clays and tonalite produced acid to intermediate melts and anorthosite residues.

One of the puzzling features of the Naauwpoort rocks is their highly potassic nature in the present area and their dominantly sodic character west of Khorixas (Frets 1969). The classic example of contrasting alkaline character of associated volcanic rocks is provided by the East African Rift System (King 1970) where lavas associated with the western rift are typically potash-rich while those farther east are soda-rich.

It is probable that one of the prime requisites for ensuring either a potassic or sodic partial melt is a parent rock of appropriate composition. In the case of acid potassic magmas an adamellitic parent would appear to be suitable [see table 4.3, column 1 (a)]. Results of alkali ion-exchange experiments conducted by Orville (1963) between vapour and feldspar would tend to confirm this. He found that if An were present, the amount of Ab in Or decreased while Ab in plagioclase and K in the vapour phase increased. Using data of Yoder, Stewart and Smith (1957), Orville also demonstrated that melt-feldspar and vapour-feldspar equilibria are very similar.

Experiments also show that residual liquids from partial melting or fractional crystallisation of tonalite under conditions of high pressure will have relatively high Ab/An ratios (Green 1969). Therefore at higher pressures the partial melting of a tonalite will produce a more calcic residue and a more sodic and Al-deficient liquid. Although a parent rock with a fairly low K/Na ratio would facilitate the production of a sodic melt, it appears necessary to infer some form of gaseous transfer of soda (Orville 1963) in order to produce rocks as sodic as those west of Khorixas.



LEGEND/LEGENDE

Nu_3	=	Okotjize Formation/Formasie Okotjize
Nnp_2	=	Upper Naauwpoort Formation/Formasie Bo-Naauwpoort
Nnp_1	=	Lower Naauwpoort Formation/Formasie Onder-Naauwpoort
Mhu	=	Pre-Nosib gneiss/Voor-Nosibgneis

Fig. 4.10 — Diagrammatic section through Summas Mountains showing the Summas Fault (indicated by a series of step faults) and the manner in which the Naauwpoort Formation originated. Block faulting was accompanied by volcanism and only when the downfaulted depression was completely filled were the volcanic deposits able to overlap onto the upfaulted gneiss.
Diagrammatiese profiel deur Summasberge wat die Summasverskuiwing toon (aangedui deur 'n reeks trapverskuiwings) en die manier waarop die Formasie Naauwpoort gevorm het. Blokverskuiwing het gepaard gegaan met vulkanisme en die vulkaniese afsettings kon die opgeskuifde gneis oordek slegs nadat die verskuiwingstrog beeltemal gevul was.

Table 4.3 COMPOSITIONS OF RESIDUE ROCKS DERIVED BY SUBTRACTION OF AN ALKALINE PARTIAL MELT FROM SELECTED CRUSTAL ROCKS†

	1	1a	2	2a	3	4	3a	3b	5	5a
SiO_2	63,90	64,90	58,50	59,10	66,20	51,90	58,20	57,00	48,40	46,70
TiO_2	1,00	1,20	1,40	1,20	0,60	1,50	0,90	0,80	1,30	1,70
Al_2O_3	15,60	15,30	15,70	16,80	15,60	16,40	17,70	19,80	16,80	17,50
Fe_2O_3	1,70	1,70	3,30	2,90	1,40	2,70	2,70	1,70	2,60	13,90*
FeO	4,60	4,90	4,00	4,10	3,40	7,00	4,20	5,10	7,90	—
MnO	0,07	0,03	0,10	0,10	0,10	0,20	0,10	0,10	0,20	0,30
MgO	2,50	1,70	2,50	2,10	1,90	6,10	2,90	3,70	8,10	7,00
CaO	5,30	5,30	5,60	5,60	4,70	8,40	6,70	5,70	11,10	10,60
Na_2O	3,50	4,30	3,40	3,50	3,90	3,40	4,00	4,00	2,30	1,40
K_2O	1,20	0,70	4,60	4,30	1,40	1,30	1,60	1,20	0,60	0,40
H_2O^+	0,30	0,20	0,40	0,10	0,70	0,80	0,40	0,70	0,60	—
P_2O_5	0,20	0,20	0,50	0,40	0,20	0,40	0,40	0,30	0,20	0,50

1—Nockolds's (1954) hypersthene-bearing tonalite.
2—Nockolds's hornblende-biotite monzonite.
3—Nockolds's average tonalite.
4—Nockolds's average diorite.
5—Nockolds's average gabbro.
1a—Hypersthene tonalite resulting from subtraction of RM 482 from Nockolds's hypersthene-bearing adamellite.
2a—Hornblende-biotite monzonite resulting from subtraction of RM 475 from Nockolds's hornblende-biotite adamellite.
3a—Undersaturated tonalite resulting from subtraction of RM 475 from Nockolds's hornblende-biotite granodiorite.
3b—Undersaturated tonalite resulting from the subtraction of Nockolds's average alkali rhyolite from the average granulite of the Canadian Shield (Eade, Fahrig and Maxwell 1966).
5a—Gabbro resulting from the subtraction of Nockolds's average alkali rhyolite from the average high-pressure granulite of the Australian Shield (Lambert and Heier 1968).

*—Total iron as Fe_2O_3.
†—It has been assumed that an arbitrary 40 per cent of the parent rock melted.

Removal of alkaline partial melts from such deep crustal rocks as Nockolds's (1954) average hypersthene-bearing adamellite (fairly high Ca and K concentrations) or his average hornblende-biotite granodiorite (high Ca, roughly equal Na and K concentrations), or even granulite (Eade, Fahrig and Maxwell 1966; Lambert and Heier 1968) would leave residues of quite normal compositions. In table 4.3 the composition of rocks thus derived are compared with some of Nockolds's averages. The correspondence is extremely good. In the case of the average granulite of the Canadian Shield (3b), the high Al content suggests that a partial melt of a rock of this composition would not be alkaline.

Partial melts with an Rb deficiency could be expected if the original parent rock were either Rb deficient (deep crustal granulites: Lambert and Heier 1968; Whitney 1969), or biotite-rich. The fact that partial melts of biotite-rich rocks will be Rb deficient is shown by high K/Rb ratios of the potash-feldspar-bearing leucosomes of migmatites (White 1966; Whitney 1969). This is readily explained by the preferential entry of Rb into biotite of the melanosome (Taylor 1965; White 1966; Whitney 1969). White (1966) also found that Ba preferred the potash feldspar to the biotite (see also Taylor 1965). Sr would be expected to follow Ba because of the close association of these two elements (Heier 1962; Taylor 1965), but since it also substitutes for Ca, it is possible that it is preferentially incorporated in one of the Ca-bearing minerals of the melanosome, i.e. plagioclase, sphene or apatite. Where a trace element can substitute for two major elements, the relationship can become very complex (Heier 1962). The fact that some granulites contain more Sr than many common crystalline rocks (Sighinolfi 1971) can probably be related to the Ca content of the granulite.

Thus a parent rock giving a biotite residue on partial melting could also give Ba-rich Rb-poor alkaline liquids. Calc-alkaline rocks of intermediate composition would appear to be the most suitable and 'are certainly common enough in shield areas.

Although it is unwise to draw far-reaching conclusions from only a limited number of analyses, two conflicting trends appear to be present within the Naauwpoort rocks which require some comment. The decreasing values for Ba, Sr, Ba/Rb and Ba/Sr and the increasing values for K/Ba and K/Sr from the base (RM 778) to the top (RM 475, RM 477, RM 482) of the Sequence could easily be accounted for if differentiation had taken place. However, there is a decrease in the total amount of Rb in the same direction, and the all-important K/Rb ratio, which should decrease with differentiation, either remains unchanged (RM 477) or increases (RM 475, RM 482). In view of the behaviour of Rb, the possibility of differentiation having occurred seems most unlikely.

The relationship of the bostonite to the rhyolites is rather difficult to explain. The bostonite may be produced from either source rocks of a slightly different composition or another magma chamber within the general zone of melting (Turner and Verhoogen 1960, p. 287). However, Middlemost (1969) suggests that the association of syenite with many epizonal and subvolcanic granites might be ascribed to preferential escape of silica along with volatiles. By this process a granitic magma gradually becomes syenitic (Emmons 1940). This mechanism could apply equally well in the present case, especially in view of the fact that extrusion of a great deal of highly siliceous rhyolite preceded eruption of the bostonite.

5. SWAKOP GROUP

The metasedimentary rocks of the Swakop Group underlie a major portion of the area. The main outcrops occur north of a line joining the Otjohorongo Granite in the east with the farm Morewag 480 in the west, and along the western edge of the area. Smaller outcrops occur on Rooipoort 414, in the vicinity of Ais village and south-west of Otjozondjou village.

5.1 STRATIGRAPHY

5.1.1 Terminology

As already indicated, a lithostratigraphic terminology has been adopted which, in table 5. 1, is compared with that currently in use as well as with recently suggested revisions. It has been proposed that the eugeosynclinal (Swakop Facies) and miogeosynclinal (Outjo Facies) successions of the former Damara "System" be renamed the Swakop and Otavi Groups*. Further revision of terms applied to all zones of rank lower than group also becomes necessary. Thus, following proposals by SACS, the two major subdivisions of the Swakop Group become the Ugab and Khomas Subgroups while sedimentary rocks forming continuous and fairly uniform sequences have been grouped together into formations and members. Where possible, well-established geographical names have been retained. Local geographical names have been used where lithological variation warrants additional subdivision.

The main stratigraphic distinction between the miogeosynclinal and eugeosynclinal facies is the presence of a distinctive sequence of mainly pelitic schist (Kuiseb Formation) at the top of the latter. The geographic name originally given to the distinctive unit of the eugeosynclinal facies (Khomas Series, Martin 1965, p. 21) is therefore retained for the group which incorporates the Kuiseb Formation, i.e. Khomas Subgroup.

Schalk and Hälbich (1965) and De Waal (196) jointly proposed that the boundary between the two major units ("Hakos" and "Khomas Series") of the "Damara System" be taken as the minor but regionally extensive unconformity at the base of the glacial unit. This has proved to be a more practical subdivision than that formerly applied, for in many localities the "Upper Hakos" marble and the Kuiseb schist interfinger and the carbonate is often even underlain by schist as in the present area. Schist below the "Upper Hakos" marble (Karibib Formation equivalent) has also been recorded by Smith (1965), Frets (1969, p. 106) and Guj (1970, p. 45). In other areas the carbonate is very thin or pinches out altogether (Martin 1965, p. 40; Hälbich 1970; present area) and the siting of this boundary becomes highly problematical. If all the schist above the Chuos Formation is included in the Kuiseb Formation, this difficulty can be eliminated. The carbonate rocks can be treated as a member (Miller 1972) or formation which either interfingers with the basal portion of the Kuiseb Formation (present area) or underlies it entirely (Jacob 1971, 1974).

The resisting of the boundary between the "Hakos Series" and "Khomas Series" also relates a major stratigraphic subdivision to the extremely persistent and useful glacial-marker unit which can be recognised throughout most of the eugeosynclinal sequence, the only exceptions being in the Otjozondjou area and in portions of the central Damara belt (Martin 1965, p. 39). In the north the long-established boundary between the two major units of the miogeosynclinal sequence is at the base of the glacial zone (Martin 1965, table V).

* SACS Working Group on pre-Cape-post-Waterberg nomenclature.

The name "Chuos Formation" eliminates such misleading terms as "Chuos Tillite" (Gevers 1931 and 1931a), "Tillite Zone" and "Tillite Substage" (Martin 1965), for as Martin points out (p. 24), most of the sediments are glaciomarine and not true tillite.

The Upper Hakos Stage of Martin's terminology (1965) is treated here as a formation that interfingers with the basal portion of the Kuiseb Formation. Local formation names have been suggested (Nash 1971 - Welwitsch Formation; Jacob 1974 - Husab Formation) but Miller (1972) and Gevers (unpublished communication, 1972) proposed that the name Karibib Formation would be historically preferable (Beetz 1929) and could be applied regionally. Additional support for this choice of name is the fact that for many years marble from this unit has been quarried near Karibib (Martin 1965, p. 139). Furthermore, these beds attain their thickest development in the Karibib District.

The Ugab Subgroup includes all sediments below the Chuos Formation and as such is only equivalent to the Lower Hakos Stage of the former terminology (Martin 1965). In the area studied the Subgroup includes three formations:

(iii) Orusewa Formation.
(ii) Okotjize Formation.
(i) Okonguarri Formation.

The Khomas Subgroup, overlying the Ugab Subgroup, is also made up of three formations:

(iii) Kuiseb Formation.
(ii) Karibib Formation.
(i) Chuos Formation.

5.1.2 Lithology

The main lithological characteristics of the lower portion of the Swakop succession up to and including the Karibib Formation are shown in the detailed sections of figures 5.1, 5.2 and 5.3, which have been made as self-explanatory as possible. Sections from the Mitten and Okotjize Folds are grouped together and those from the vicinity of the Summas Mountains form a separate but comparable group.

5. 1 .2. 1 *Ugab Subgroup*

The metasedimentary rocks of the Ugab Subgroup flank the Ais Dome, the Mitten Fold and the eastern and southern portions of the Summas Mountains. They overlie the Huab Complex north of the Summas Mountains and also form the cores of the Rondehoek and Okotjize Folds and the anticline south-west of Otjozondjou village. North and east of the Summas Mountains they form a conformable interfingering succession with the volcanic rocks of the Upper Naauwpoort Formation. Farther south a slight discordance is developed in places between these rocks and the Lower Naauwpoort extrusives. A major unconformity separates the Ugab rocks from the Huab Complex.

On lithological evidence the Ugab Subgroup in the area south of 20° 30' has been subdivided into a lower Okotjize Formation and an upper Orusewa Formation. The thickness of the Subgroup tends to mirror the thickness of the Okotjize Formation as it is by far the thicker of the two subdivisions. North of 20° 30', however, on Sienna 70 and Minorca 71, the Gaseneirob Formation consisting

Table 5.1 TERMINOLOGY USED FOR THE SUBDIVISIONS OF THE DAMARA SEQUENCE IN THE AREA STUDIED*

<table>
<tr><th colspan="4">Smith (1965), Martin (1965)</th><th colspan="3">Hälbich (1970)</th><th colspan="3">Jacob (1971), Nash (1971)</th><th colspan="4">Present investigation</th><th rowspan="2">Thickness (m)</th></tr>
<tr><th>System</th><th>Series or Formation</th><th>Stage</th><th>Substage</th><th>System</th><th>Series or Formation</th><th>Stage</th><th>Group</th><th>Subgroup</th><th>Formation</th><th>Sequence</th><th>Group</th><th>Subgroup</th><th>Formation</th></tr>
<tr><td rowspan="6">DAMARA</td><td>Khomas Series</td><td></td><td></td><td rowspan="6">DAMARA</td><td rowspan="3">Khomas Series</td><td>Windhoek</td><td rowspan="6">DAMARA</td><td rowspan="3">Khomas</td><td>Witpoort in west
Tinkas in east</td><td rowspan="9">DAMARA</td><td rowspan="6">SWAKOP</td><td rowspan="3">Khomas</td><td>Kuiseb</td><td>Maximum 9 800</td></tr>
<tr><td rowspan="5">Hakos Series</td><td rowspan="2">Upper Hakos</td><td></td><td>Auas</td><td>Husab</td><td>Karibib</td><td>1 000</td></tr>
<tr><td>Tillite</td><td>Onnaams</td><td>Chuos</td><td>Chuos</td><td>3–200</td></tr>
<tr><td colspan="2">Unconformity</td><td colspan="2">Unconformity</td><td colspan="2">Unconformity</td><td colspan="3">Unconformity</td></tr>
<tr><td rowspan="2">Lower Hakos</td><td rowspan="2"></td><td rowspan="2">Hakos Series</td><td>Berghof</td><td rowspan="2"></td><td rowspan="2">Rössing</td><td rowspan="2">Ugab</td><td>Orusewa</td><td>0–120</td></tr>
<tr><td>Verloren</td><td>Okotjize</td><td>100—>900</td></tr>
<tr><td colspan="4">Conformable transition
UNCONFORMITY</td><td colspan="3">UNCONFORMITY</td><td colspan="3">UNCONFORMITY</td><td colspan="4">UNCONFORMITY, local conformable transition</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">Nosib Formation</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">Rehoboth Formation</td><td rowspan="2"></td><td rowspan="2">NOSIB</td><td rowspan="2"></td><td>Khan</td><td rowspan="2">NOSIB</td><td rowspan="2"></td><td rowspan="2">Naauw-poort</td><td rowspan="2"></td></tr>
<tr><td>Etusis</td></tr>
</table>

* For comparison, nomenclature currently in use (Martin 1965) as well as recently suggested revisions are also given.

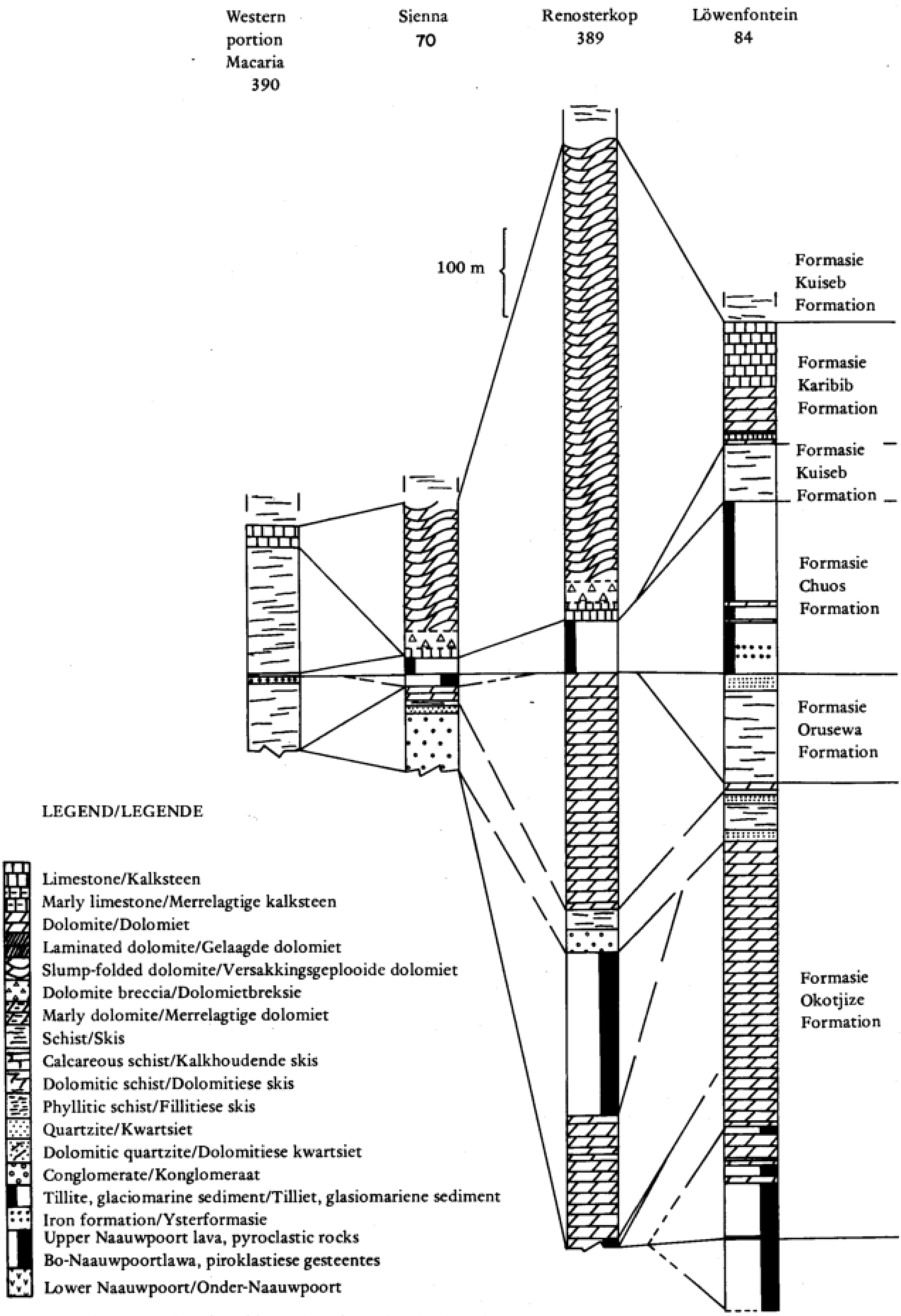


Fig. 5.1 — Stratigraphic sections from the vicinity of the Summas Mountains.
Stratigrafiese profiele in die omgewing van die Summasberge.

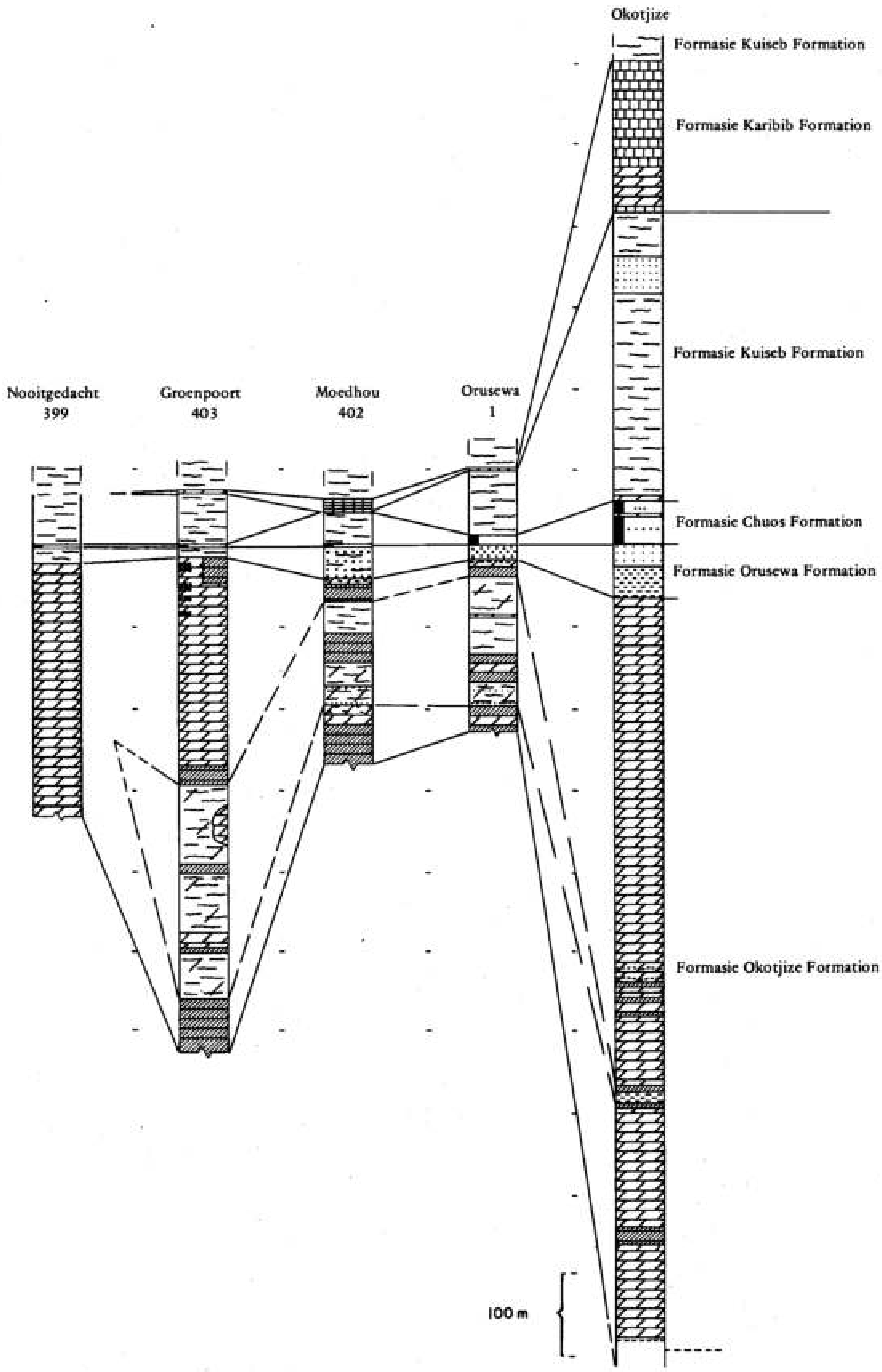
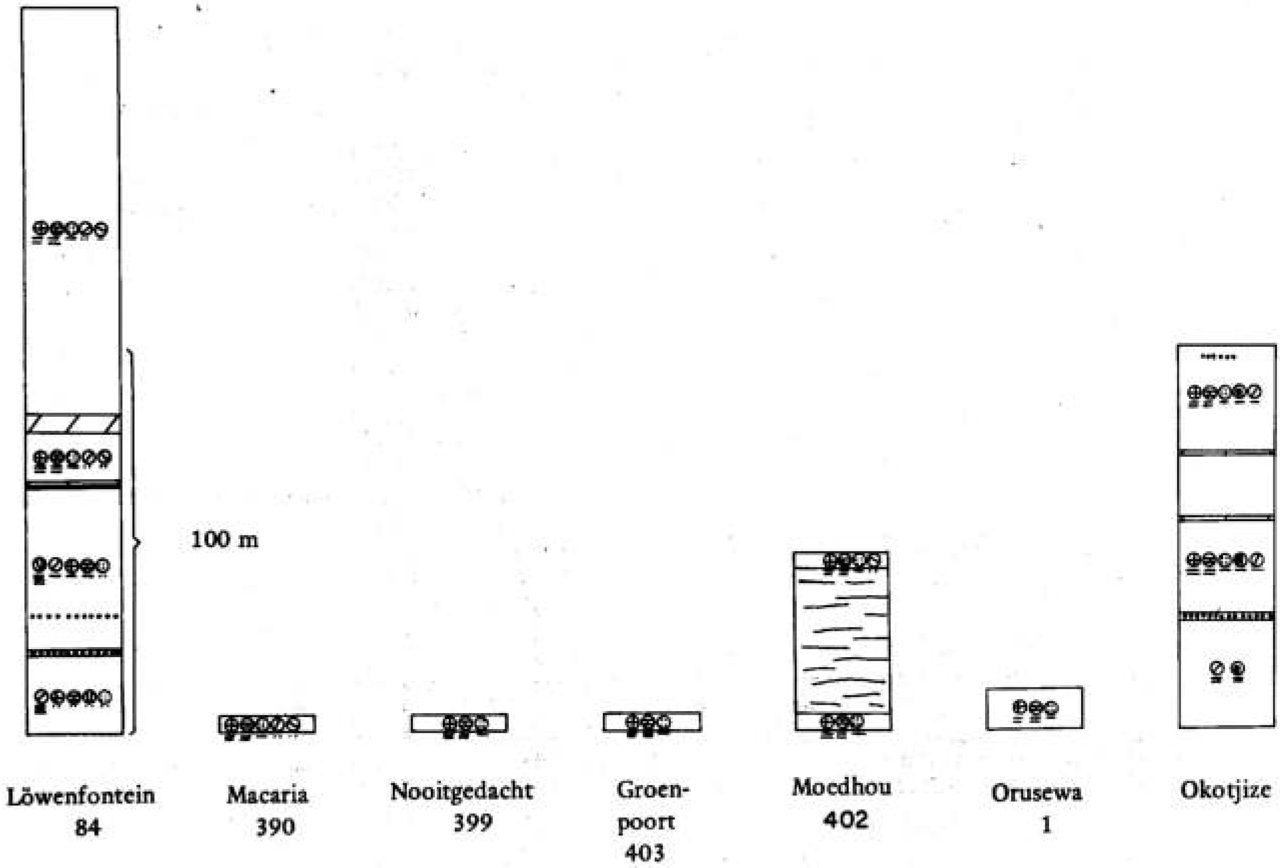


Fig. 5.2 — Stratigraphic sections from the margin of the Mitten Fold and from the eastern limb of the Okotjize Fold. For legend see figure 5.1.
Stratigrafiese profiele van die rand van die Mittenplooi en van die oostelike uitloper van die Okotjizeplooi. Vir legende kyk figuur 5.1.



LEGEND/LEGENDE

Lithology/Litologie

- Tillite/Tilliet
- Dolomite/Dolomiet
- Iron formation/Ysterformasie
- Schist/Skis

Inclusions/Insluitsels

- Granite/Graniet
- Gneiss/Gneis
- Dolomite/Dolomiet
- Quartzite/Kwartsiet
- Rhyolite/Rioliet
- Schist/Skis
- Quartz/Kwarts

Subscripts/Onderskrifte

- Very abundant/Oorvloedig
- Abundant/Volop
- Common/Algemeen
- Very rare/Baie skaars

Fig. 5.3 – Details of pebble inclusions in the Chuos Formation.
Besonderbede van rolsteeninsluitsels in die Formasie Chuos.

of schist with minor intercalations of quartzite and sandy limestone, underlies the Okotjize Formation tectonically. The exact stratigraphic position' of this unit is not known but the rocks are tentatively correlated with the Okonguarri Formation (Clifford 1967). It is also possible that the unit is part of the Mulden Group.

5.1.2.1.1 *Okotjize Formation*. - Despite a fairly variable lithology, the same general sequence can be recognised throughout the area. The Formation is made up largely of dolomite which in many places contains intercalations of foliated schist and marly schist. In most sections these schistose sediments occur roughly halfway up in the succession. In the north, conglomerate and arkose are associated with the schist. Thin basal quartzite and arkose occur on the south-eastern edge of the Mitten Fold, on the farm Sebraskop 410 and due east of Ais village. Very thin beds and laminae of chert occur locally in the dolomite.

The whole unit is relatively thin (200 m to 600 m) in the region of the pre-Swakop Naauwpoort Ridge (see previous chapter) but thickens appreciably in an easterly direction to a maximum in excess of 900 m in the Okotjize Fold. In the thick sections schist is either very minor or altogether absent but it makes up a considerable portion of the succession in three of the sections from the Mitten Fold and is therefore rather well developed where the Formation itself is thinnest.

Post-depositional erosion accompanying the Chuos glaciation removed the whole of this Formation from the southern margin of the Summas Mountains.

The dolomite is usually light- or dark-grey in colour but north and east of the Summas Mountains it is mainly white or light-brown. The beds in the upper 450 m and lower 50 m of the succession in the Okotjize Fold and the upper 40 m of the Karstenville sections are white. Bedding usually varies from massive to thin but locally, where the unit is compressed, laminated dolomite is abundant (Orusewa and Moedhou sections).

Most of the dolomite contains small amounts of arenaceous and pelitic impurities but in many of the beds in the region between Moedhou and Orusewa this detrital material becomes quite abundant. An increase in grain size of the dolomite from north to south has been induced by metamorphism and this is accompanied by the appearance, in the impure dolomites, of calc-silicate minerals which become abundant in the skarns flanking the Ais Dome.

A rather interesting feature is the intercalation of five siliceous iron formation beds at the top of the dolomite on Groenpoort 403. These alternate with brown dolomite in the lower portion and ferruginous schist and dolomite in the upper portion. The beds are thickest on the central part of the farm where they form a total of 29 m of a 55-m-thick stratigraphic section. Farther east the iron formation occurs higher up in the succession and forms part of either the Orusewa or Chuos Formations.

The schist and marly schist intercalated in the succession in the north are associated with the conglomerate zone shown in the Renosterkop section. Arkose accompanies the schist on Löwenfontein 84 and on the western portion of Rondehoek 83. Farther south the greater thickness of the schist and the intercalated dolomite beds suggest that accumulation covered a longer time span than that which is represented by the detrital sediments in the north.

Thin sections show that well-aligned muscovite is the most abundant micaceous mineral but small amounts of biotite are also present. A good deal of the schist contains variable amounts of dolomite and/or calcite. In the skarns flanking the Ais Dome fairly thick layers containing large amounts of scapolite are probably equivalent to the marly schist farther north.

Conglomerate is restricted to the succession north of the Summas Mountains and occurs either at the base or is interbedded higher up in the succession. The thickest unit occurs on the central portion of Renosterkop 389 where an estimated 500 m of conglomerate is present. These rocks are quite unsorted in the west and contain a large proportion of angular inclusions which generally do not exceed 30 em in diameter (fig. 5.4). To the east the conglomerates become bimodal and are composed of approximately equal proportions of lithic inclusions and fine-grained schistose matrix (fig. 5.5). Most beds are oligomictic and contain only inclusions of foliated Huab gneiss. Locally, there are scattered boulders of white quartzite and, near the Summas Mountains, Naauwpoort volcanic rocks. The latter are more angular than the accompanying boulders of gneiss. The units on Sienna 70 and the northern portion of Renosterkop 389 become finer grained towards the top and eventually grade into graywacke and/or schist. Only in the finer-grained layers of these northernmost outcrops does bedding become apparent. The coarse-grained conglomerate is always massive. These features indicate that the conglomerates have been derived from the immediate vicinity by very rapid erosion. The Summas Fault and the numerous subsidiary faults associated with it were still active at this stage. Scarps which were produced by the final movements on these faults were the probable source of the conglomeratic material.

The arenaceous sediments are arkose or feldspathic quartzite. The arkose is associated with the schist in the Löwenfontein section. It is poorly sorted and contains highly strained quartz, saussuritised plagioclase which often has bent twin lamellae, a little perthite and a considerable amount of fresh chess-board albite (An_o). A few lithic fragments are also present. Contacts between quartz grains and between quartz and matrix are highly sutured. The felspathic quartzite shows both poor and reasonably good sorting. It contains minor amounts of microcline perthite and saussuritised plagioclase (An_{25-35}) as well as accessory quantities of muscovite, biotite, ore, tourmaline, rutile and zircon. Rare grains of chess-board albite occur.

5.1.2.1.2 *Orusewa Formation*. - This mainly schistose Formation is thin but persistent and attains its thickest development of 120 m on the eastern flanks of the Summas Mountains. It follows conformably on the Okotjize Formation but along the southern margin of the Summas Mountains, where this is absent, it rests discordantly on Lower Naauwpoort volcanics. Only in the two northernmost sections is the Orusewa Formation absent. Quartzite is present at the top of the Löwenfontein and Okotjize sections and siliceous iron formation occurs south of the Summas Mountains and around the eastern arm of the Mitten Fold. Thin fine-grained dolomite lenses are also present at the top of the Formation south of the Summas Mountains and all around the Mitten Fold.

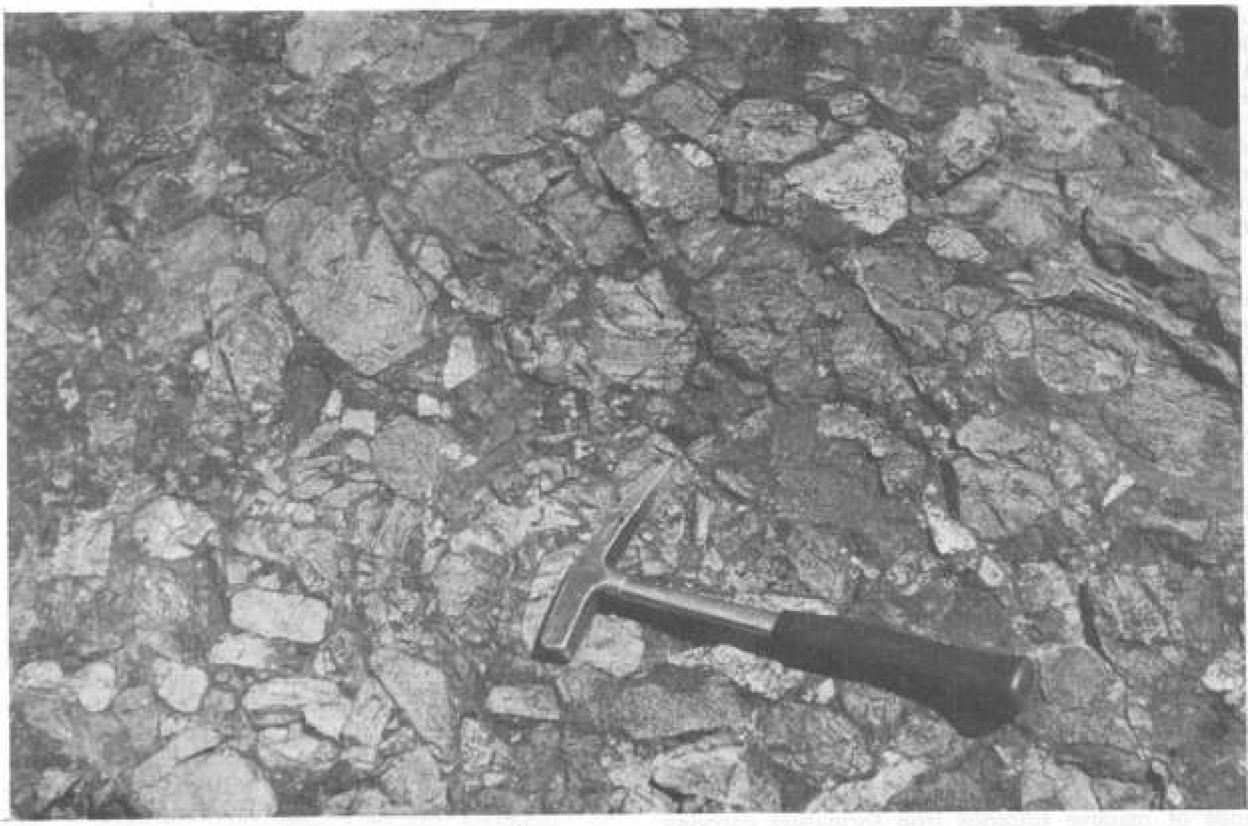


Fig. 5.4—Unsorted oligomictic Okotjize Formation conglomerate with a very high proportion of angular and subangular gneiss inclusions derived from the Huab Complex. Sienna 70.
Ongesorteerde oligomiktiese konglomeraat van die Formasie Okotjize met 'n baie hoë persentasie van hoekige en amperhoekige gneisinsluitsels afkomstig van die Kompleks Huab. Sienna 70.

Fig. 5.5—Bimodal Okotjize Formation conglomerate consisting of approximately equal proportions of unsorted inclusions and fine-grained schistose matrix. Inclusions are mainly Huab gneiss with minor Naauwpoort rhyolite. Central portion Renosterkop 389.
Bimodale konglomeraat van die Formasie Okotjize wat omtrent gelyke hoeveelhede van ongesorteerde insluitsels en fynkorrelrige skisagtige matriks bevat. Insluitsels is hoofsaaklik Huabgneis met ondergeskikte Naauwpoortrioliet. Sentrale deel Renosterkop 389.

The schist is similar in many respects to the foliated schist of the overlying Kuiseb Formation. However, in the Okotjize Fold it is not as highly metamorphosed as in the rest of the area and is phyllitic. In thin section it is seen to be made up mainly of very fine quartzo-feldspathic grains but also contains a fairly large proportion of muscovite orientated parallel to the foliation. Small amounts of biotite and ore are also present.

The quartzite shows considerable variation in thickness of bedding and is extremely variable in composition and texture. It is either very fine grained or gritty. Certain layers contain more dolomite than quartz, others contain major quantities of both microcline and plagioclase. Sorting is both poor and very good. Angular and well-rounded grains can occur together. Muscovite is usually present as well as lesser amounts of biotite and accessory ore and zircon. The stratigraphic position and variable nature of the quartzite suggest that it may represent some of the earliest finer-grained deposits produced by glacial erosion elsewhere, but it lacks large angular inclusions which could be taken as proof of a glacial origin.

The iron formation usually forms separate beds within the schist. These vary from two (Macaria 390) to five (Moedhou 402) in number and from 1 cm to 4 m in thickness. However, on Orusewa 1 the whole of the Orusewa Formation carries iron. Here bands of massive siliceous iron formation carrying about 60 per cent hematite/magnetite ore, grade into foliated ferruginous schist which contains between 10 and 20 per cent iron ore.

5.1.2.1.3 *Highly metamorphosed equivalents of Ugab Subgroup*. - The layered skarn overlying the Naauwpoort metavolcanics in the Ais Dome and the poorly exposed reconstituted rocks which form the core of the anticline in the south-eastern corner of sheet 2015C, have been included in the Ugab Subgroup on the basis of their mineralogical composition which reflects the chemical characteristics of the Ugab Subgroup sediments farther north. Relative thicknesses also conform to the regional changes in thickness established farther north. The abundant layered calc-silicate rocks of the Ais Dome are probably equivalent to the dolomitic sediments of the Okotjize Formation. In the latter case, the association of marble and calc-silicate rock with abundant lit-par-lit granite and pegmatite bodies suggests an original lithology similar to the 4000-m-thick dominantly schistose sequence below the glacial unit in the Okonguarri Anticline (Clifford 1962). This unusual sequence may be equivalent to the Ugab Subgroup.

5.1.2.2 *Khomas Subgroup*

Metasedimentary rocks of the Khomas Subgroup occur mostly north of a line joining the Otjohorongo Granite in the east of sheet 2015C with the farm Morewag 480 in the west of sheet 2014D. There is also a fairly large outcrop on the western edge of the latter sheet.

Around the Mitten Fold the exact nature of the contact between the schist at the top of the Ugab Subgroup and the schistose glaciogenic rocks at the base of the Khomas Subgroup has been obscured by the development of a pronounced foliation which has destroyed bedding. The transition appears to be conformable. The succession is also conformable in the Okotjize and Rondehoek Folds and also the southern and eastern flanks of the Summas Mountains. A slight discordance exists between the sediments of the two Subgroups in the outcrops north of the Summas Mountains. Glacial erosion produced the unconformity at the base of the Orusewa Formation along the southern margin of the Summas Mountains.

Glaciogenic metasedimentary rocks of the Chuos Formation form the base of the Subgroup. These are overlain by a very thick sequence of schist (Kuiseb Formation) which has a regionally important carbonate unit near its base (Karibib Formation). Higher up in the succession there are local intercalations of quartzite and dolomite. Over the major part of the area, the thickness of the Subgroup is determined largely by the thickness of the Kuiseb Formation but where this is absent, as for example north of the Summas Mountains, the Karibib Formation becomes the important unit.

5.1.2.2.1 *Chuos Formation*. - Outcrops of the Chuos Formation are limited to the Mitten and Okotjize Folds and to the vicinity of the Summas Mountains. In the crestal regions of the pre-Swakop Naauwpoort Ridge, nearly all deposits are very thin (Macaria, Groenpoort and Nooitgedacht sections) but they become far thicker and show a more complete record on the eastern flanks of this structure. The following sequence, recorded from top to bottom, occurs near the southern boundary of Löwenfontein 84:

Table 5.2 SEQUENCE OF THE CHUOS FORMATION

	m
Tillite; massive, schistose matrix. Inclusions angular, unsorted, 0,5-60 cm in diameter in lower 40 m, less than 3 cm in diameter in upper 80 m; mainly quartzite, gneiss and granite, very rare dolomite and pelitic metasediment, no inclusions of lava	120
White micritic dolomite, no inclusions, weathers to a light yellowish-brown colour	5
Tillite, as above	12
White micritic dolomite, as above	1,5
Laminated dolomitic schist, no inclusions	0,6
Tillite, massive, schistose matrix. Inclusions angular, unsorted, 0,5-60 cm in diameter (larger sizes fairly common); Naauwpoort lava very abundant, dolomite less abundant than below, quartzite, gneiss and granite also present	35
Siliceous iron formation, no inclusions	0,3
Tillite, very similar to the 35-m-thick tillite above	8
Siliceous iron formation, no inclusions	1,3
Tillite, massive, matrix dolomitic but becomes schistose near the top. Inclusions angular, unsorted, 0,5-40 cm in diameter, mainly dolomite, very rarely lava, granite and gneiss	19

Almost exactly the same succession occurs in the Okotjize Fold but there are in addition thin lenses of iron formation near the top of the unit and a 6-m-thick bedded unit of fluvioglacial origin at the base which contains rounded but unsorted pebbles of dolomite and chert.

The inclusions in all outcrops are quite unsorted and generally range in size from 0,5 to 60 cm, but in the Sienna and Renosterkop sections several large boulders of Fransfontein granite with diameters of 1 m occur. On the whole, angular and subangular inclusions predominate but in most of the area there is also a fairly large proportion of rounded and subrounded fragments. Granite, gneiss and quartz are the main types of inclusions but in the lower portions of the Löwenfontein and Okotjize sections lava and/or dolomite predominate (fig. 5.3). On Sebraskop 410 the lower portion of the Formation is ferruginous. Most of the deposits in the crestal regions of the Naauwpoort Ridge are equivalent to the lower 40 m of the 120-m-thick tillite zone in the Löwenfontein section because large granitic and gneissic inclusions are abundant in both.

The matrix of the Formation is predominantly schistose but in the lower portions of thick sections it is dolomitic where dolimite inclusions are abundant. In thin sections the schistose matrix can be either strongly or only very weakly foliated. Quartz and feldspar, the main constituents, are accompanied by variable amounts of chlorite, biotite and muscovite. Grains making up the coarser fraction of samples are mostly angular to subangular, unsorted and irregular in shape.

A glaciomarine origin for most of the unit is indicated by the restriction of pre-depositional erosion to the Summas Mountains region and by the large subrounded boulders of granite and gneiss (up to 1 m in diameter) that are sparsely scattered throughout the schistose matrix of most outcrops. The only typical tillite occurs in the Löwenfontein section where unsorted, angular and subangular inclusions of all shapes and sizes are set in an abundant massive fine-grained matrix.

The thin layers of micritic dolomite and siliceous iron formation found in the Löwenfontein section indicate that there were at least four temporary retreats of the ice sheets during which non-glacial sediment was able to accumulate. These may have been fairly general because one iron formation layer and both dolomite layers were also found in the Okotjize Fold. Furthermore, thin lenses of an identical white very fine-grained dolomite occurring at the top of the Orusewa Formation in the Macaria, Nooitgedacht and Orusewa sections are highly probable equivalent to the dolomite layers on Löwenfontein 84. It is significant that the glacial deposits of these sections are equivalent to the tillite immediately overlying the dolomite layers on Löwenfontein.

An interesting analogy can be found in very persistent marker beds of pink dolomite, 1 m thick, at the top of the tillitic deposits in the Adelaidean of Australia (Dunn, Thomson and Rankama 1971). These are believed to represent a very precise period during the deposition of the tillite. *

The Chuos Formation serves as an extremely useful marker horizon which is sandwiched between the carbonates of the Okotjize Formation and the Karibib Formation. Where one of these zones is missing, the presence of the Chuos Formation enables the other zones to be identified without any difficulty, but where the Chuos Formation is not exposed or cannot be found (as for example around the Ais Dome and in the anticline south-west of Otjozondjou village), then correlation with the units of the established sequence becomes somewhat speculative. The Chuos Formation can readily be located in most parts of the area because of the close association of iron formation which either forms prominent ridges or a distinctive scree.

5.1.2.2.2 *Karibib Formation*. - The Karibib Formation forms the core of the Okongwe Fold and is the uppermost carbonate in the succession in the Okotjize and Rondehoek Folds and north and north-east of the Summas Mountains. In the crestal regions of the Naauwpoort Ridge it is either very thin or altogether absent. It is best developed east of the Naauwpoort Ridge and reaches a thickness of 190 m in the Okotjize Fold. In the Okongwe Fold and north and north-east of the Summas Mountains post-depositional slumping and interference folding have resulted in a greatly exaggerated thickness.

The zone varies from thickly bedded to laminated. Beds are usually grey in colour but white layers also occur (fig. 5.6). Dolomite makes up most of the lower half of the Löwenfontein and Okotjize sections. The upper half is composed almost entirely of limestone with only a few thin beds of dolomite. In the crestal regions of the Naauwpoort Ridge the Karibib Formation consists mainly of limestone but this

* Personal communication, 1971, Prof. K. Rankama, University of Helsinki.

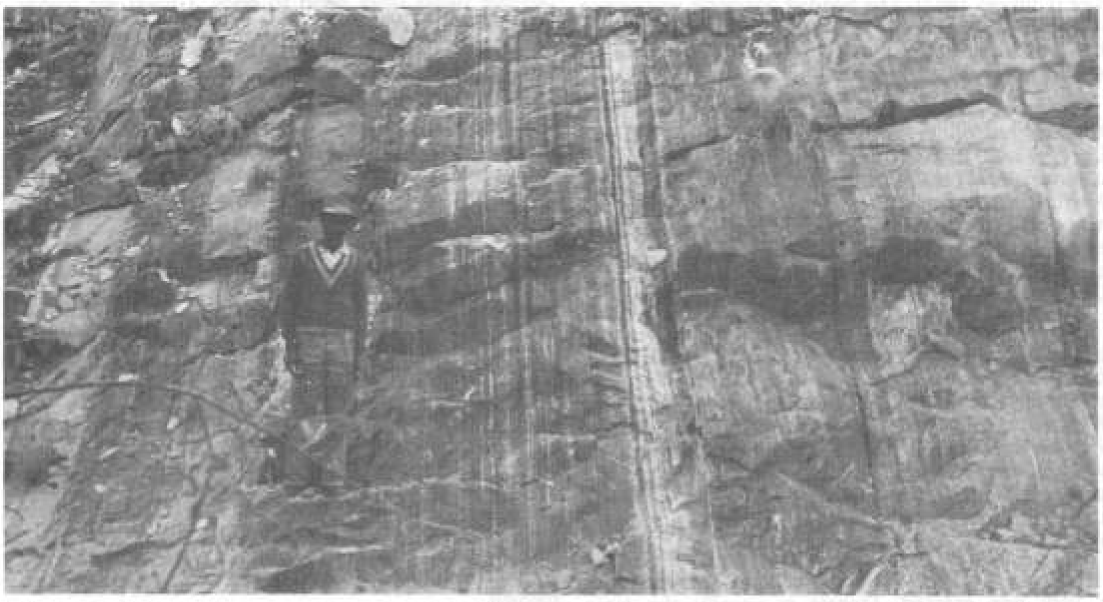


Fig. 5.6—Thickly bedded to very thinly bedded Karibib Formation limestone. Eastern margin, Okotjize Fold. Facing north; beds dip very steeply to the east.
Dikgelaagde tot baie dungelaagde kalksteen van die Formasie Karibib. Oostelike rand van die Okotjizeplooi. Blik na die noorde; lae hel baie steil na die ooste.

grades into dolomite on Groenpoort 403. Very thin chert beds are associated with the upper portion of the sequence where it is thick and with the whole sequence where thin.

The Karibib Formation north of the Summas Mountains differs quite considerably from the sequence in the rest of the area. Thinly bedded limestone and a few oolitic chert lamellae make up the lowest 10 m. This is followed by a breccia 30 m thick, composed of unsorted angular fragments of massive and bedded dolomite set in a massive dolomite matrix. Fragments at the base of this can be traced to underlying partially disrupted beds. The breccia is overlain by highly contorted, often slightly brecciated, massively bedded dolomite. Most folds within this unit are developed on a mesoscopic scale and, though very irregular, have uneven subhorizonial axes. Overturned structures are numerous and almost all have axial planes inclined to the south. The breccia and folds within the overlying dolomite strongly suggest that slumping occurred in the partially consolidated sediments during post-depositional uplift. On Braunfels 387 and Minorca 71 neither the breccia nor the slump structures are developed.

Frets (1969) has noted the development of a similar breccia near Fransfontein and Guj (1974) has shown that it is intermittently developed along the whole southern edge of the Kamanjab Inlier. In all these occurrences, the overlying sequence is more strongly deformed than the underlying rocks with structures suggesting slumping in a southerly direction. The breccias and slump structures indicate that the Summas Mountains region and the Kamanjab Inlier were positive structures at some stage prior to complete consolidation.

Comparison with other areas shows that the beds on Sienna 70 correspond fairly well to the bedded lime-stone-breccia-massive dolomite succession flanking the Kamanjab Inlier (Frets 1969) and the limestone-massive dolomite sequence of the Okonguarri Anticline (Clifford 1962). The bedded dolomite underlying the limestone east of the Naauwpoort Ridge is therefore somewhat unusual and would appear to be only a local development.

The main carbonate of the anticline south-west of Otjozondjou village is made up of between 80 and 100 per cent calcite. Dolomite is very minor and only very few calc-silicate minerals have developed. Detrital quartz grains have remained unaffected by metamorphism in some samples. Chemical characteristics therefore indicate that these calcitic marbles are probably equivalent to the limestone of the Karibib Formation.

5.1.2.2.3 *Kuiseb Formation*. - Most of the outcrop area of the Swakop rocks are underlain by metasedimentary rocks of the Kuiseb Formation. These are mostly mica schists but include very minor quantities of quartzite and dolomite. The top of the sequence, as is the case in the rest of the eugeosynclinal area, has been eroded away, but the preserved succession has a maximum determinable thickness of 9 800 m in the area between the villages of Okenyenya and Ondundojiuapa.

The mica schist is foliated and either fine grained or very fine grained. Quartz is usually the main constituent followed by well-orientated mica and then by feldspar. In some specimens mica is the major component. In most of the area muscovite, the main micaceous mineral, is accompanied by variable but significant amounts of primary chlorite. Biotite and secondary chlorite are only very minor or accessory constituents. The primary chlorite is length-fast and has a very weak anomalous brownish-grey bire-fringence indicating a dominance of Mg over Fe (Albee 1962). On the other hand, the length-slow character and anomalous blue birefringence of the secondary chlorite indicate a greater content of Fe than Mg. Feldspars, usually slightly weathered, are most difficult to identify in these fine-grained rocks and only plagioclase (An_{0-8}) has been detected.

With the increase in metamorphic grade nearer the Salem granite, biotite has developed at the expense of chlorite and muscovite. This in its turn breaks down close to the granite to yield cordierite and untwinned perthitic potash feldspar. The higher-grade schist contains only very little muscovite and is composed instead of quartz, biotite and, in places, cordierite and feldspar.

In table 5.3 the modes and partial modes of the coarser-grained samples are given. It has unfortunately not been possible to obtain reliable modal analyses of the finer-grained samples. The present mineralogy of the schist (over 60 thin sections have been examined) indicates that the original succession consisted of approximately equal proportions of graywackes or subgraywackes and shales.

Thin quartzite beds are intercalated with the schist in the Okavakua and Okenyenya Synclines, in the core of the Ondundo Anticline and on Uitskot 395. Thicker beds are fairly numerous in the Dagbreek Syncline. Most are very light grey on fresh surfaces but weather to a light-brown colour. Those in the core of the Ondundo Anticline are a drab grey-green. The Dagbreek Syncline quartzites are the only ones that contain a few pebbles.

Thin sections show minor to accessory quantities of plagioclase, calcite and microcline perthite and accessory amounts of muscovite, biotite, ore, apatite, zircon and tourmaline (Ondundo quartzite excepted). Sorting varies from good to poor. Grains are highly strained and contacts strongly sutured. In a few specimens there is a tendency for a granoblastic mosaic texture to develop.

The quartzite in the core of the Ondundo Anticline differs from the other occurrences in that it contains fairly large quantities of euhedral to subhedral tourmaline (ω - colourless, ε - very light-yellow) and a few aggregates of very fine-grained epidote. Because of the good crystal form of tourmaline, it is no longer possible to tell whether it was an original constituent of the sediment or whether it was introduced at some later stage. The epidote is a product of low-grade metamorphism.

The dolomite intercalations occur on the western edge of the area where beds can be as much as 280 m thick. In the rest of the area a few very thin lenses of dolomite, usually less than 10 em thick, occur locally in the schist. In the west the dolomites are coarse grained, white or grey in colour and both massively and thinly bedded. Metamorphism has induced a complete recrystallisation but reaction between dolomite and siliceous impurities has only taken place nearer the granite, where tremolite, scapolite, diopside, garnet and wollastonite have formed.

A pre-tectonic dolerite intrusive that occurs as a resistor in the Salem granite will be dealt with under the heading of metamorphism.

Table 5.3 MODES AND PARTIAL MODES OF COARSE-GRAINED SAMPLES OF KUISEB FORMATION SCHIST AND SUBGRAYWACKE

<table>
<tr><th>Sample</th><th>Quartz</th><th>Potash feldspar</th><th>Plagioclase</th><th>Muscovite</th><th>Biotite</th><th>Chlorite</th><th>Cordierite</th><th>Carbonate</th><th>Ore</th><th>Accessory minerals</th></tr>
<tr><td>Low-grade samples:</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>RM 211.........</td><td>57</td><td colspan="2">28</td><td>2</td><td>13</td><td>—</td><td>—</td><td>—</td><td>—</td><td>Apatite</td></tr>
<tr><td>RM 690.........</td><td>53</td><td colspan="2">13</td><td>9</td><td>9</td><td>9</td><td>—</td><td>4</td><td>2</td><td>Zircon, Apatite, Tourmaline</td></tr>
<tr><td>High-grade samples:
RM 315.........</td><td>—</td><td>—</td><td>—</td><td>2</td><td>46</td><td>—</td><td>—</td><td>—</td><td>—</td><td></td></tr>
<tr><td>RM 458.........</td><td>43</td><td colspan="2">32</td><td>1</td><td>20</td><td>2</td><td>—</td><td>1</td><td>1</td><td>Apatite, Tourmaline</td></tr>
<tr><td>RM 461.........</td><td>28</td><td colspan="2">10</td><td>5</td><td>29</td><td>—</td><td>—</td><td>28</td><td>—</td><td>Apatite, Tourmaline, Sillimanite</td></tr>
<tr><td>RM 652.........</td><td>30</td><td colspan="2">14</td><td>5</td><td>26</td><td>—</td><td>—</td><td>24</td><td>—</td><td>Ore, Tourmaline</td></tr>
<tr><td>RM 815.........</td><td>—</td><td>—</td><td>—</td><td>2</td><td>21</td><td>—</td><td>—</td><td>—</td><td>—</td><td></td></tr>
<tr><td>RM 830.........</td><td>39</td><td>—</td><td>21</td><td>—</td><td>40</td><td>—</td><td>—</td><td>—</td><td>—</td><td>Ore, Apatite, Tourmaline</td></tr>
</table>

5.2 FACIES CHANGES

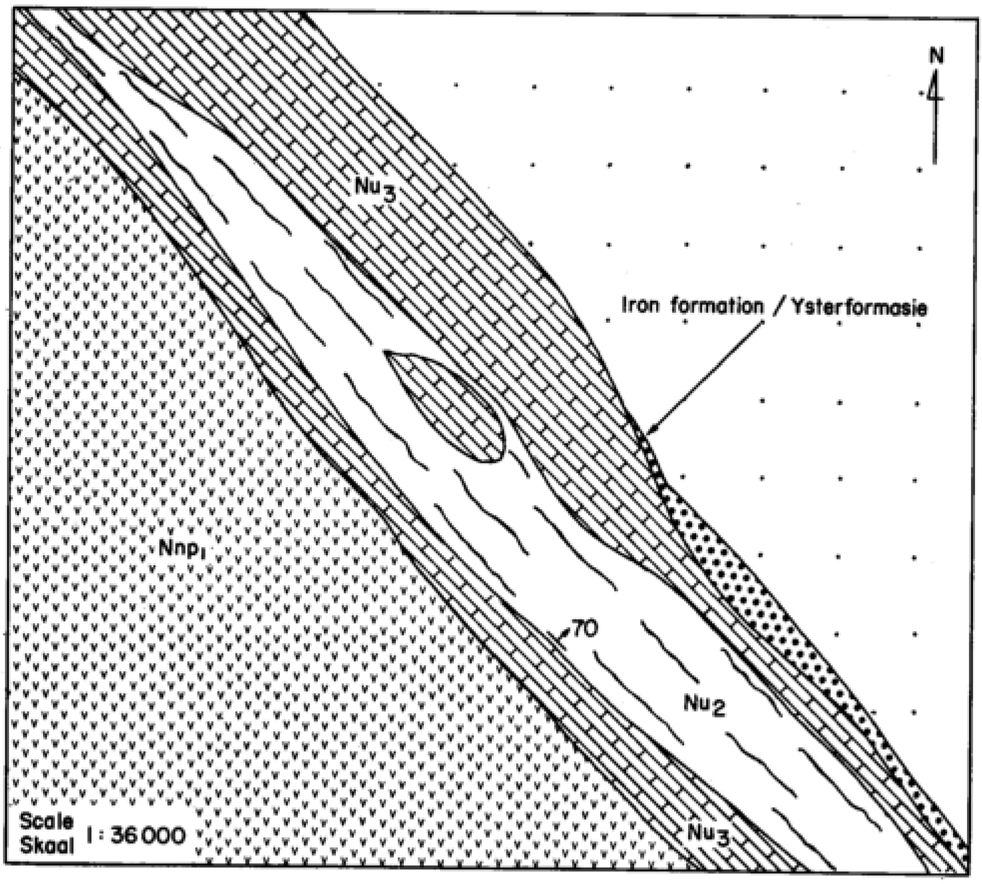
The Swakop Group has been subdivided solely according to lithostratigraphic criteria, but the discussion of facies changes immediately bring in the time factor, for without it no lateral lithological change can be proved. The only time-rock unit in the whole Swakop succession is the glaciogenic Chuos Formation. This is not as suitable a time marker as such "instant rocks" as bentonites, but it nevertheless owes its origin to unusual climatic conditions which on a geological time scale are generally only of limited duration. Even allowing for glacial advances and retreats, the relative time factor will not vary greatly from place to place. On a large scale the major units above and below the Chuos Formation will bear the imposition of a loose chronostratigraphic correlation, but on a small scale, time correlations must be limited to the beds directly in contact with the Chuos Formation. The pronounced thickness changes of a formation are bound to be accompanied to some extent by facies changes, but this can only be proved in the case of the Orusewa and Chuos Formations. For the rest it is only possible to show lithological changes of well-defined units and most of these have already been described in the section on lithology.

The most obvious facies change in the Okotjize Formation is the gradation from bedded and massive dolomite in the east into laminated dolomite in the crestal regions of the Naauwpoort Ridge. This is accompanied by a decrease in thickness of the whole unit. The sudden disappearance of the iron formation beds occurring at the top of this Formation in the central portion of Groenpoort 403 coincides with a very rapid increase in the thickness of the immediately underlying dolomite which loses its laminated character and becomes massive. These two features, together with the huge interstratified dolomite body in the underlying marly schist (fig. 5.7), strongly suggest that the dolomite is a barrier-reef deposit which prevented the accumulation of iron formation farther to the west. The fact that neither reef talus nor stromatolitic structures (present in the Khorixas area - Frets 1969) were found can be attributed to recrystallisation of the dolomite during post-Damara metamorphism. Probable biohermal deposits in the west are therefore coeval with laminated dolomite and iron formation farther east.

Intraformational conglomerates north of the Summas Mountains have psammitic and pelitic equivalents in the Löwenfontein section and quite probable farther south as well, but in the latter case it is not possible to show time equivalence.

The most interesting facies change concerns the Orusewa and Chuos Formations. Outcrops of the latter around the Mitten Fold contain only granite, gneiss and quartzite inclusions, many of which are of fairly large size (maximum 60 em). A comparison with the most complete section of the Chuos Formation (Löwenfontein) shows that granitic and gneissic inclusions only become abundant in the upper portions. Thus the earliest glacial deposits, characterised by inclusions of dolomite and lava, are not developed farther south. This immediately suggests that the upper portions of the Orusewa Formation are pelitic equivalents of the lowermost deposits of the Chuos Formation. Further support for this is provided by the two thin persistent non-glacial beds of white micritic dolomite which occur throughout all the thicker glacial deposits at the base of the zone containing abundant granitic inclusions. In the compressed sections on top of the Naauwpoort Ridge these dolomites are found as intermittent lenses in the schist a metre or two below the Chuos Formation. The probable precise time significance of these dolomite beds has been alluded to in an earlier section.

The main iron formation beds are always found just below these thin dolomite zones irrespective of whether they occur in the Orusewa Formation or the Chuos Formation and they therefore give some indication of the time equivalence. The correlation cannot be carried too far, however, because conditions suitable for the deposition of iron formation existed on a limited scale very early on (in places nearly the whole of the Orusewa Formation is ferruginous) and per-



LEGEND/LEGENDE

Nu_3	=	Okotjize Formation/Formasie Okotjize
Nu_2	=	Okonguarri Formation/Formasie Okonguarri
Nnp_1	=	Lower Naauwpoort Formation/Formasie Onder-Naauwpoort

Fig. 5.7 — Sketch from an aerial photograph of two thick deposits of Ugab Subgroup dolomite which probably represent reef accumulations. The rapid lensing of the iron formation coincides with the sudden increase in thickness of the underlying dolomite. Central portion, Groenpoort 403.
Skets vanaf 'n lugfoto van twee dik afsettings van dolomiet van die Subgroep Ugab wat waarskynlik rifafsettings is. Die vinnige uitknyping van die ysterformasie stem ooreen met die skielike toename in dikte van die onderliggende dolomiet. Sentrale gedeelte, Groenpoort 403.

sisted until a very late stage as the iron formation lenses at the top of the Chuos Formation in the Okotjize section indicate (see also Martin 1965, p. 30).

In the Moedhou section two thin glaciomarine beds are separated by 40 m of schist which entirely lacks inclusions. The proximity of the uppermost bed to the carbonates of the Karibib Formation does indicate the possibility that at least some of the schist at the very base of the Kuiseb Formation is coeval with the youngest Chuos Formation deposits.

Periods of coeval deposition of schist and carbonate, and schist and quartzite, are indicated by the pinching-out of the Karibib Formation in the west and by the presence of regionally restricted beds of dolomite and quartzite higher up in the Kuiseb Formation.

5.3 TRANSITION BETWEEN THE SWAKOP AND OTAVI GROUPS

The lower portion of the Swakop Group is, on a large scale, lithologically very similar to almost the whole of the Otavi Group. Lithological continuity exists between the two and the intercalation of the Chuos Formation shows that there is a very close time correlation (Martin 1965). Several features indicate that in both areas deposition took place in shallow water.

In the north these features are: (1) the abundance of carbonate, most of which is chemical in origin (Martin 1965, p. 31); (2) abundant and widespread stromatolitic structures in certain zones (Martin 1965; Krüger 1969) - in a few places these are enclosed in rocks that give off a fetid odour when hammered; (3) oolitic chert.

In the south, shallow water is indicated by: (1) the pinching-out of the earliest deposits against ‘islands’ which formed part of the uneven floor of the depositional basin; (2) locally derived inclusions in the Chuos Formation (Smith 1965; Jacob 1974); (3) abundant carbonates which are most unlikely to have a deep-water origin (all deep-sea carbonates forming at the present time are made up of the tests of pelagic organisms), and (4) disseminated graphite flakes in certain zones and the fetid odour of the enclosing rocks (both very probable of organic origin).

Thus the comparable lithologies of these two large basins indicate that initially both were subsiding at more or less the same rate, but that a somewhat greater amount of sediment accumulated in the north (Martin 1965, table 5). These basins were partially separated from each other by a relatively immobile ridge-now the Kamanjab Inlier - over the extremities of which the two seas coalesced.

Following the deposition of the Karibib Formation in the south, the rate of subsidence in that region began to increase. This was accompanied by a large increase in the supply of detritus. In the north, on the other hand, the rate of subsidence remained more or less the same and shallow-water carbonate deposition continued (Tsumeb Subgroup). It was therefore at this stage that the main facies difference between the Otavi and Swakop Groups developed. However, it is not possible -in the light of present knowledge to indicate how much of the Tsumeb carbonate in the north is coeval with the Kuiseb schist.

Subsidence which enabled the Kuiseb schist to accumulate took place from the edge of the Kamanjab Inlier. This feature-the geanticlinal ridge-is therefore the boundary between the miogeosynclinal and eugeosynclinal basins but typical miogeosynclinal carbonate rocks with marker beds of highly characteristic stromatolites still lie along the southern margin of the Kamanjab Inlier (Fransfontein Ridge).*

The facies boundaries on the Geological Map of South West Africa (1963) have therefore been placed too far south and actually include portions of the eugeosynclinal facies deposited on the southern flank of the geanticlinal ridge in the miogeosynclinal facies. It is of interest to note that many of these boundaries actually coincide with zones where there is a marked and rapid decrease in the grade of regional metamorphism. This is, however, a later feature and has nothing to do with the original stratigraphy.

The author therefore considers all the sediments south of the Fransfontein Ridge, excluding those belonging to the Mulden Group, to be included in the Swakop Group.

6. MULDEN GROUP

Sedimentary rocks of the Mulden Group form two small outcrops in the vicinity of the Löwenfontein River on Olifantshoek 388 and Renosterkop 389. The base of the succession is not exposed and the size of the outcrops is severely limited by a Tertiary to Quaternary cover of calcrete. The exposed succession is made up entirely of light greenish-grey very fine-grained schist which contains a few thin lenses of light-brown limestone. The main constituents of the schist are quartz, muscovite and chlorite. Biotite, ore and calcite are accessory minerals.

The Mulden schists have been strongly folded along east - west axes. The beds dip mainly southwards at high angles but there are also a few small parasitic folds with westerly plunging axes. Two very poor cleavages are developed. One dips very steeply south-west and the other dips westwards at a moderate angle. In contrast to the well-foliated Khomas schist, the Mulden schist appears massive in the field. In thin section there is a well-developed alignment of micaceous minerals. A comparison of the two schists quite clearly shows that the Mulden schist has undergone a much lower grade of meta-morphism.

In the Huab-Khorixas area Mulden sedimentary rocks rest unconformably on carbonate rocks of the Swakop Group (Frets 1969) as well as the Kuiseb schist (Guj 1974). Frets (1969) was able to show that the rocks were deformed during the later stages of the F_2 phase of post-Swakop folding and in the present area the Mulden succession has been similarly affected.

Erosion was probably very active during uplift which accompanied the F_1 phase of post-Swakop folding. It is probable that the F_1 deformational phase merged into the F_2 phase and that erosion was continuous throughout. However, towards the closing stages of the first phase, sediment began to accumulate in intermontane areas and in deeply eroded regions. During the F_2 phase of folding these sediments were also subjected to folding.

* Personal communication, N. Thirion, Tsumeb Corporation Limited.

7. CORRELATION AND AGE OF SWAKOP AND MULDEN GROUPS

The correlation with units farther south is shown in table 5.1. The Ugab Subgroup is only correlative with the Lower Hakos Stage of the former nomenclature (Martin 1965). The Khomas Subgroup includes both the "Upper Hakos Stage" and the "Khomas Series". Within this Subgroup the Chuos Formation of the new terminology is equivalent to the "Tillite Substage", the Karibib Formation to the "Upper Hakos Stage" and the Kuiseb Formation to the "Khomas Series". As indicated earlier, well-established geographical names of the different units have been retained where possible.

The fact that the Chuos Formation is developed in the Okonguarri Anticline to the east of the present area (Guj 1974) indicates that the underlying Kabussemjama Member (Clifford, Nicolaysen and Burger 1962) is the equivalent of the Ugab Subgroup and possibly more specifically the Orusewa Formation, because carbonates are missing altogether from this sequence. The underlying Okonguarri Member containing mainly psammitic and pelitic metasediments with subordinate dolomite, has been tentatively correlated by Clifford with the Khan quartzites of the Nosib Group in the Khan-Swakop area. It is rather unusual then that lithological equivalents of the dolomitic Okotjize Formation or of the Uranus Member (Clifford, Nicolaysen and Burger 1962) should be entirely missing. However, five of the nine units of interbedded dolomite of the Okonguarri Member are well developed and very persistent and in view of this the unit should be included in the Ugab Subgroup. A point in favour of this interpretation is the fact that no Naauwpoort pyroclastic rocks (which have a late Nosib to early Swakop age) have been found interbedded in the Okonguarri Member. The present distance of 50 km between the core of the Okonguarri Anticline and the Summas Mountains (the point at which extrusion took place) is less than the distance between the two most widely separated outcrops of Naauwpoort rocks in the present area (60 km).

In the north-east of the area, continuous outcrops exist between the U gab Subgroup and the Uranus Member of Clifford, Nicolaysen and Burger (1962), the Chuos Formation and the Landeck Member, the Karibib Formation and the Bergriede Member, and the Kuiseb Formation and the Okaua Member.

The Ugab Subgroup, Chuos Formation and at least part of the Khomas Subgroup are respectively the eugeosynclinal equivalents of the Abenab Subgroup, Chuos Formation and Tsumeb Subgroup of the Otavi Group farther north.

Söhnge (1964) and Clifford (1962) have suggested that the Otavi valley phyllite and the upper Tsumeb Subgroup dolomites may be equivalent to part of the Khomas schist farther south. The Otavi valley phyllite is identical to the Mulden phyllite in the Tsumeb area and it is underlain by quite typical Mulden-type quartzite. The succession does not differ from the Mulden Group and must be correlated with it. No interfingering of the upper Tsumeb Subgroup carbonate rocks (zone 8) with their characteristic oolitic cherts and Mulden rocks has ever been observed. From north to south in the Tsumeb area the relationships remain the same, i.e. Mulden quartzite or phyllite overlying Tsumeb zone 8 dolomite and oolitic chert. This relationship still holds in the Otavi valley which is the farthest south for these two units to occur and only 20 km north of typical Kuiseb schist. Therefore, the upper Tsumeb sequence does not undergo a facies change to more pelitic rocks towards the south, and in the Tsumeb area there is nothing to indicate lateral equivalence of the. Kuiseb schist with either the upper Tsumeb rocks or the Mulden Group.

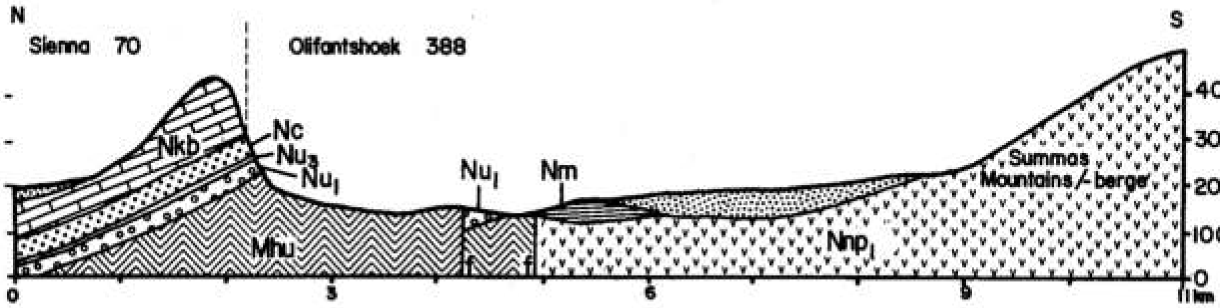
The relationship between Kuiseb schist and the Mulden rocks is apparent in the Summas Mountains (sheet 2015C). The contact between the Karibib Formation and the overlying Kuiseb schist is conformable throughout the area mapped by the author. This contact is exposed along the eastern and southern margins of the Summas Mountains. The nearest Mulden rocks occur a mere 9 km away at a stratigraphic level well below the above contact. The topography of figure 7. 1 indicates that uplift and removal by erosion of the Karibib and Chuos Formations and Ugab Subgroup, as well as part of the Naauwpoort Formation and Huab gneiss, preceded deposition of the Mulden rocks. The unconformable relationship between the Mulden and Swakop Group rocks is in marked contrast to the conformable upper contact of the Karibib Formation with the Kuiseb schist and indicates that the Mulden Group is younger than the Kuiseb schist.

The post-F_1-pre-F_2 erosion with preceded deposition of the Mulden Group is well displayed west of Fransfontein where Mulden-filled gorges cut deep into Otavi dolomite and pre-Otavi basement (Frets 1969). On Austerlitz 515 in the same area, Mulden rocks rest unconformably on a thick sequence of Kuiseb schist that is conformably underlain by rocks equated with the Tsumeb Subgroup (Guj 1974).

Cloud and Semikhatov (1969) have correlated stromatolites in the Abenab Subgroup of the Otavi Group with forms in North Africa and Siberia for which approximate ages are known. They bracket the Abenab Subgroup stromatolites between 0,6 and 600 and 1 200 Ma. The U/Pb age of zircons from porphyries of the Naauwpoort Formation which underlie dolomite of the Okotjize Formation is between 720 and 750 Ma (Burger and Miller, in preparation).

The minimum age of the Mulden Group can be deduced from the relationship of the Salem granite to structural fabrics in the area. The Mulden Group was deposited subsequent to the first relatively gentle phase of deformation (accompanied by exposure and erosion in the Fransfontein area), but prior to the second phase (S_2 fabrics) which was very intense (Frets 1969) and which coincided with or just preceded the peak of regional metamorphism (see chapter 9). The intrusive, differentiated portions of the Salem granite give a whole-rock Rb-Sr age of 540 Ma (Hawkesworth, Miller and Roddick, in preparation), which is comparable to the Rb-Sr age of 545 to 570 Ma of stilpnomelane that crystallised in the Fransfontein granite 30 km to the north during post-Damara regional metamorphism (Clifford 1967). The Salem granite cuts the S_2 fabric in the Kuiseb schist (Miller 1974). The main phase of deformation (F_2) occurred after deposition of the Mulden Group but prior to intrusion of the late differentiates of the Salem granite. The Mulden Group is probably significantly older than 540 Ma.

Redistribution of Rb and Sr in rocks of the Fransfontein Suite between 1 100 and 1 300 Ma ago is attributed to erosion that immediately preceded deposition of the Otavi Group (Clifford, Nicolaysen and Burger 1962).



LEGEND/LEGENDE

Nm	=	Mulden Group/Groep Mulden
Nkb	=	Karibib Formation/Formasie Karibib
Nc	=	Chuos Formation/Formasie Chuos
Nu_3, Nu_1	=	Okotjize Formation/Formasie Okotjize
Nnp_1	=	Lower Naauwpoort Formation/Formasie Onder-Naauwpoort
Mhu	=	Pre-Nosib/Voor-Nosib

Fig. 7.1 – Relationship of the Mulden Group to the Naauwpoort Formation and Lower Swakop Group north of the Summas Mountains.
Verbouding van die Groep Mulden tot die Formasie Naauwpoort en die Groep Onder-Swakop noord van die Summasberge.

8. STRUCTURE OF THE SWAKOP GROUP

8.1 INTRODUCTION

Several phases of tectonic activity have affected the rocks of the Swakop Group. The earliest were syndepositional but very minor. The first of the main post-depositional phases of deformation (F_1 to F_4) produced large flexure folds with roughly east-west-trending axes and wavelengths of several kilometres. The second phase, almost at right angles to the first, was far more intense and developed in three stages. The third and fourth phases were relatively minor and are only locally developed. All four phases, F_1 to F_4, were recognised by Frets (1969) in the Huab-Khorixas area to the north-west.

8.2 TERMINOLOGY

	1st Phase	*2nd Phase*	*3rd Phase*	*4th Phase*
Phase...........	F_1	F_2	F_3	F_4
Bedding.........	s_0	s_0	s_0	s_0
Cleavage........	—	early-s_1, s_{1a} late-s_2	s_3	s_4, s_5
Intersection lineation		$l_1 - s_2/s_1$ $l_2 - s_2/s_0$	$l_3 - s_3/s_2$	

All structural data shown on stereographic projections have been plotted on the lower hemisphere of a Schmidt net.

8.3 FEATURES RESULTING FROM SYNDEPOSITIONAL UPLIFT

Two disconformities, one developed at the base of the U gab Subgroup along the flanks of the Mitten Fold and the other, more marked than the first, occurring below the Chuos Formation along the south-eastern margin of the Summas Mountains, point to periods of gentle but local uplift during sedimentation.

Thick slump breccias in the upper horizons of the Karibib Formation on Sienna 70 formed when the dolomite was in a semi-consolidated state. They thus indicate a third gentle syndepositional uplift of the geosynclinal floor, probably in the region of the Summas Mountains.

8.4 POST-SEDIMENTATION STRUCTURES

8.4.1 F_1 structures

A roughly north-south compression resulted in the development of flexure folding of several large approximately east-west-trending asymmetrical anticlinal and synclinal structures with wavelengths of several kilometres. These structures only occur on a macroscopic scale and are not accompanied by any penetrative cleavage or lineation. In the Mitten, Okotjize, Okongwe and Rondehoek Folds the traces of the refolded F_1 axes are for the greater part of their length now parallel to nearby F_2 axes.

On Minorca 71 the sequence has been repeated by several refolded thrusts. The schists, and in places the dolomite, are intensely sheared. Shearing has been so intense that the granitic inclusions in the Chuos Formation are foliated parallel to the cleavage in the enclosing schist-a phenomenon found nowhere else in the area mapped. It is impossible to ascertain whether thrusting was the result of syndepositional basin ward slumping or F_1 folding. The thrust planes are refolded about the F_2 axes.

8.4.2 F_2 structures

The prominent structures in the area are products either of the F_2 folding alone (Ondundo Anticline, Dagbreek, Okenyenya and Okotjandjoura Synclines) or of the combined effects of F_1 and F_2 folding (Mitten, Okotjize, Okongwe and Rondehoek Folds). East of the Mitten Fold axial planes of structures have north-north-east trends and are steeply inclined (to the east in the Okapereka Syncline and the north-western branch of the Okotjize Fold, and to the west in the Okavakua and Okenyenya Synclines and Okongwe Fold) or subvertical (southern portion of Ondundo Anticline, Okotjandjoura Syncline). West of the Mitten Fold the orientation of structures changes to north-west and axial planes dip largely to the south-west. Structures with subvertical axial planes occur on the southern portion of Delta 400 in the vicinity of the Salem granite.

The present work together with regional mapping by Clifford (1962), Frets (1969) and Guj (1974) in areas to the north-east and north-west indicates that on a regional scale the change in axial direction of the F_2 folds is the result of adjustments to the form of the geanticlinal ridge represented by the Kamanjab Inlier (fig. 8.1) 30 km to the north (Frets 1969, p. 210, regards the Summas Mountains as part of the geanticlinal ridge), and the pre-Swakop Naauwpoort Ridge which extended southwards into the geosyncline at an angle of almost 90° to its margin and which is now represented by the Summas Mountains, the Mitten Fold and the Ais Dome. It is across this feature that the change in axial direction of the F_2 folds takes place (fig. 8.1).

The Naauwpoort Ridge actually played an important role in the whole post-Naauwpoort evolution of the area. During the F_1 folding the Ridge developed huge crustal undulations but it subsequently acted as a barrier of uneven height against which the overlying Swakop rocks became tightly compressed during the F_2 folding. Low points in the barrier have produced local complications and distortions in the F_2 structures.

Various features indicate that F_2 structures developed in three successive stages during a single, more or less continuous though locally variable, compression.

8.4.2.1 *Stage 1*

Plunges on all folds can largely be ascribed to differential vertical movements along fold axes and would be expected to be reasonably similar in folds from anyone area. However, axial plunges of the F_2 folds in all non-interference structures [32° or less, figs 8.2 (a) and (b), 8.3 (a) and (b)] are not as great as those of the F_1 folds (42° to 70°, figs (8.4, 8.5, 8.6 and 8.7). It is quite reasonable to expect that an initial plunge developed in the F_1 folds while they were still parallel to the direction of maximum F_2 compression, i.e. east-west.

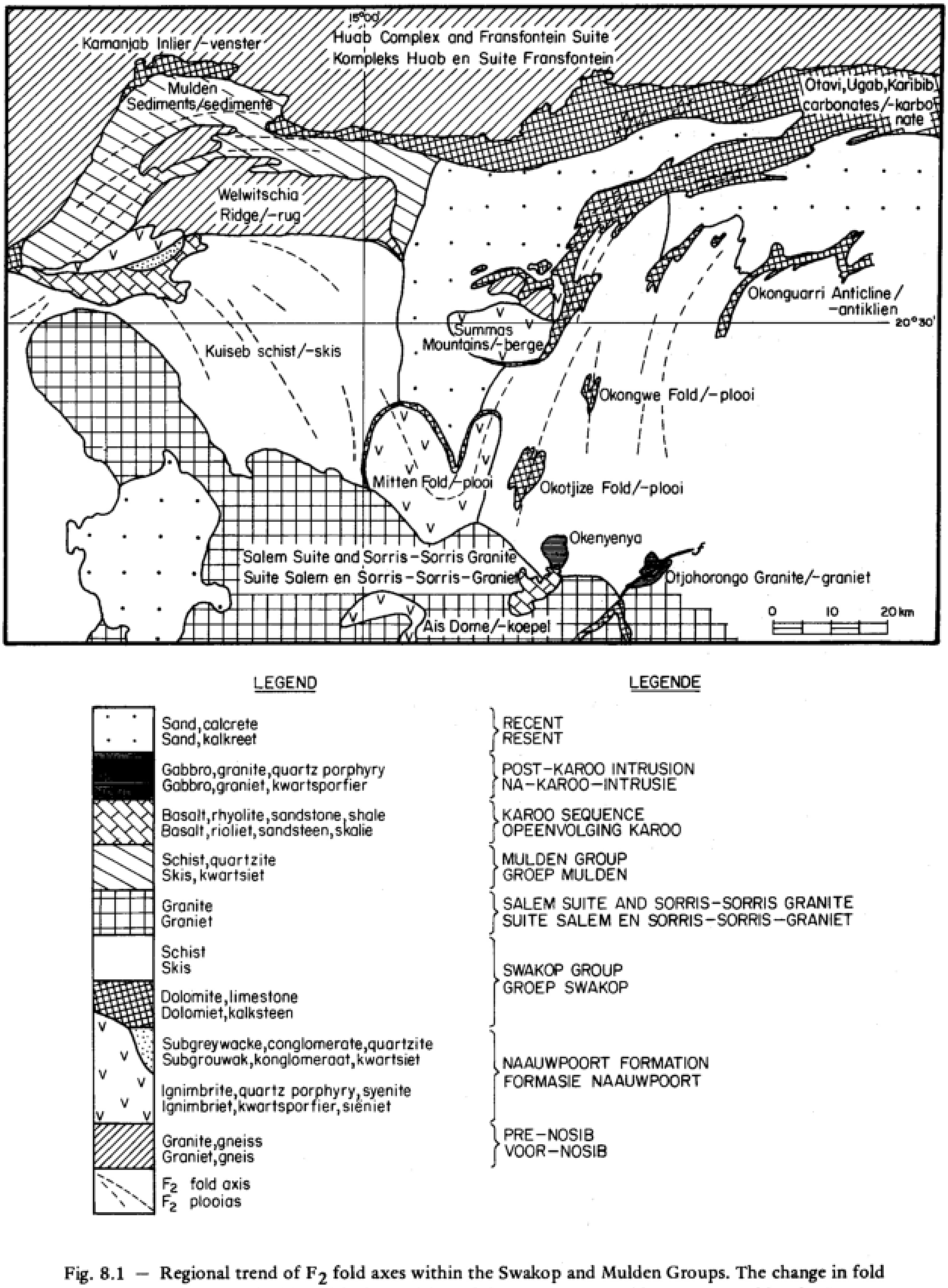
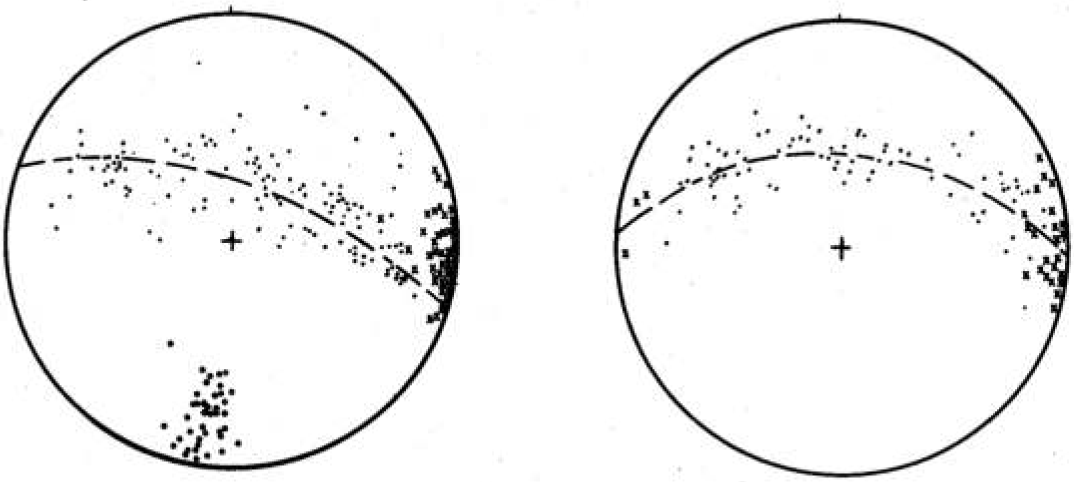


Fig. 8.1 — Regional trend of F_2 fold axes within the Swakop and Mulden Groups. The change in fold direction coincides with the position of the Naauwpoort Ridge represented by the Summas Mountains, Mitten Fold and Ais Dome.
Regionale strekking van F_2 plooiasse in die Groepe Swakop en Mulden. Die verandering in plooirigting stem ooreen met die ligging van die Naauwpoortrug verteenwoordig deur die Summasberge, Mittenplooi en Aiskoepel.



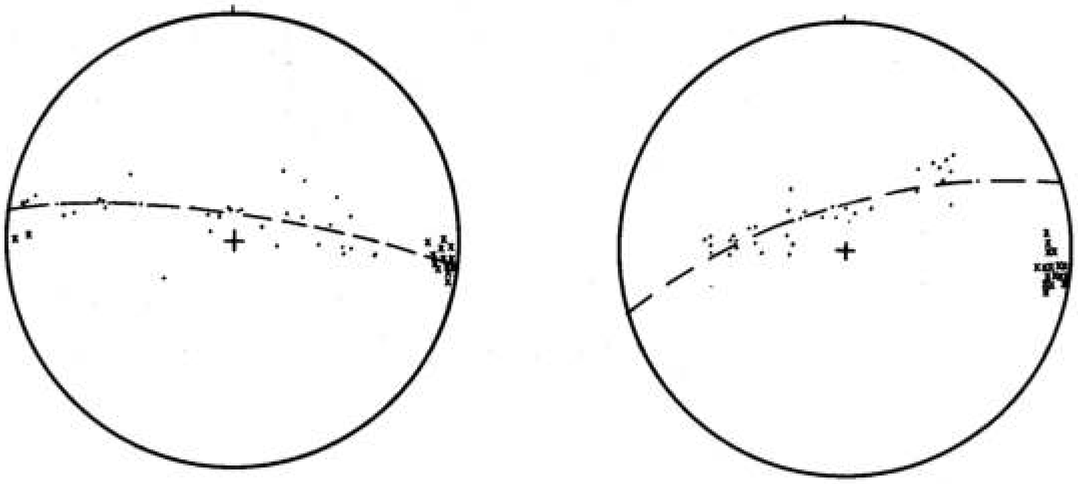
a b

· Bedding/Gelaagdheid

x s_2

• l_2-, s_2/s_0 lineation/-lineasie

Fig. 8.2 — Structural data from the Ondundo Anticline: (a) in the vicinity of Ondundojiuapa, (b) from a minor synclinal fold on the eastern limb of the main structure.
Struktuurgegewens van die Ondundo-antiklien: (a) naby Ondundojiuapa, (b) van 'n klein sinklinale plooi op die oostelike uitloper van die hoofstruktuur.



a b

· Bedding/Gelaagdheid

x s_2

Fig. 8.3 — Structural data from the Okotjandjoura Syncline: (a) northern portion, (b) southern portion.
Struktuurgegewens van die Okotjandjourasinklien: (a) noordelike deel, (b) suidelike deel.

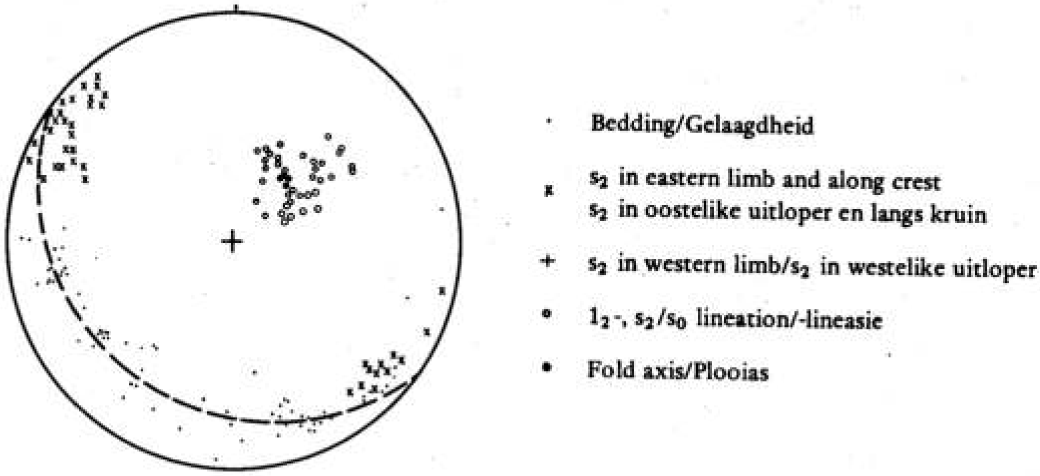


Fig. 8.4 – Structural data from the north-western nose of the Okotjize Fold.
Struktuurgegewens van die noordwestelike neus van die Okotjizeplooi.

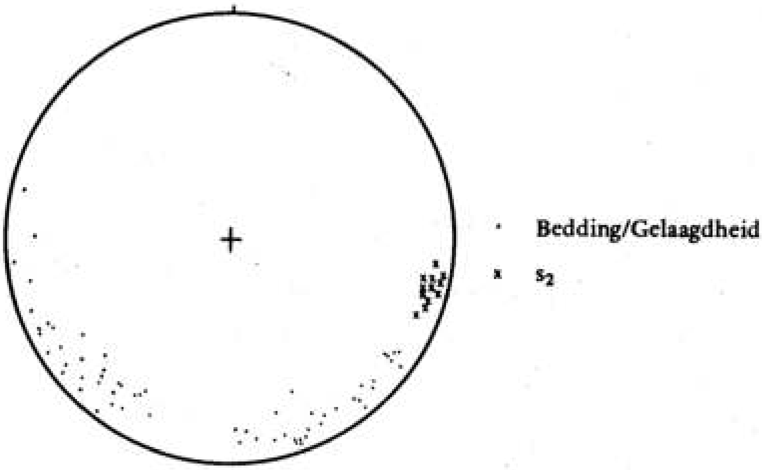


Fig. 8.5 – Structural data from the F_1 nose of the Rondehoek Fold.
Struktuurgegewens van die F_1-neus van die Rondehoekplooi.

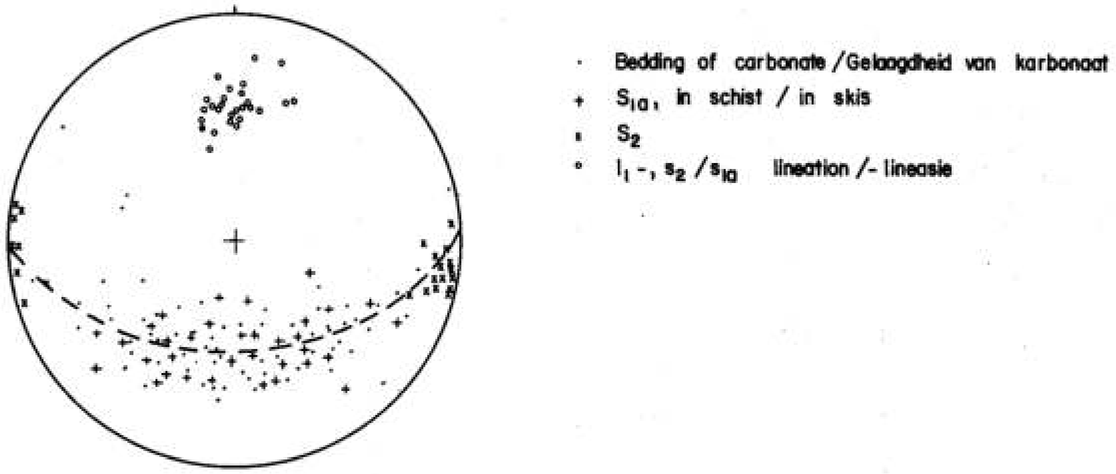


Fig. 8.6 – Structural data from the north-eastern nose of the Mitten Fold.
Struktuurgegewens van die noordoostelike neus van die Mittenplooi.

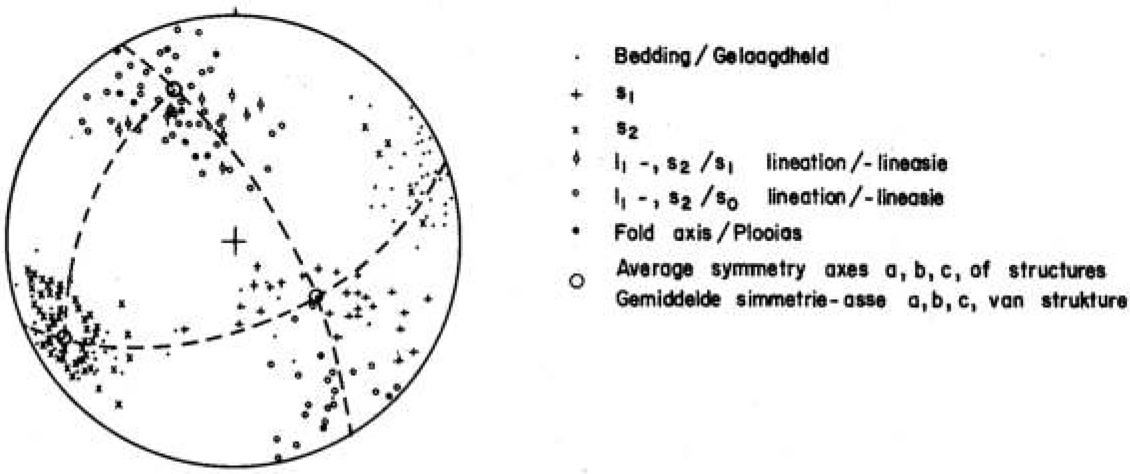


Fig. 8.7 – Structural data from several minor folds on Nooitgedacht 399 and the southern portion of Delta 400. Axial plunges are very variable resulting in the variable attitude of l_2. The s_1 cleavage is only developed in north-westerly plunging fold closures.
Struktuurgegewens van verskeie ondergeskikte plooie op Nooitgedacht 399 en die suidelike deel van Delta 400. Asduikings varieer baie en gee aanleiding tot 'n veranderlike stand van l_2. Die s_1-kliewing is slegs ontwikkel in die geslote strukture wat na die noordweste duik.

The easterly increase in thickness of the Lower Damara sedimentary rocks away from the hump of the Naauwpoort Ridge -does suggest the possibility of an even earlier plunge resulting from deposition on a gently sloping floor. Once the F_1 axes had become bent, subsequent vertical movements would merely enhance any existing plunge. Axes of those F_1 folds that bent least of all (Summas Mountains Fold and the north-eastern nose of the Rondehoek Fold) have very steep plunges (up to 83°) as a result of their having been orientated nearly parallel to the direction of maximum F_2 compression for the full duration of that phase (fig. 8.5).

All major F_2 structures would have started forming during this stage, probably by flexure folding but indications of this mechanism have been destroyed by later shear folding.

8.4.2.2 *Stage 2*

There must have been a considerable amount of differential movement in the schist between the comparatively immobile Summas Mountains Fold and the Mitten Fold during the bending of the F_1 axis of the latter. This was accompanied by a relative east to west movement of material through low points in the barrier-forming north-south Naauwpoort Ridge and a tightening of folds along its western flank. The movement, clearly indicated by the two bent fold axes south of the Summas Mountains, took place by means of shearing along bedding planes and resulted in the development of a bedding parallel slip cleavage (s_1) in the schist. This cleavage has only been observed on Delta 400 where it is poorly developed, and on Orusewa 1 and Macaria 390 where it is the dominant cleavage. Around the two F_1 noses of the Mitten Folds, S_1 follows the dip of the underlying carbonate rocks (figs 8.6 and 8 .7). Further F_2 compression has, however, contorted S_1 surfaces by different amounts in different localities.

On Orusewa 1 the S_1 surface is rather sinuous but still reflects the attitude of the major structure. On Delta 400, however, later minor folds have been compressed into isoclinal structures in which S_1 can only be recognised in the axial regions (fig. 8.7). In the limbs of these folds, S_1 cannot be distinguished from the later S_2 cleavage, to which it is parallel.

In the parasitic folds of the western limb of the Okapereka Syncline (fig. 8.8) a few layers of micaceous quartzite occur in the schist. The S_1 cleavage is well developed in the schist but is not present in the quartzite. Instead an axial-plane cleavage (S_{1a}) is developed in the latter [figs 8.9 (a) and (b)] which is entirely confined to the axial regions of the folds. The strike of this cleavage changes as the trend of the fold axis changes. Recrystallised biotite is concentrated in and parallel to the S_{1a} cleavage planes.

Field observations indicate that during this stage the greatest amount of shearing and recrystallisation of the schist took place in the region of the Orusewa nose of the Mitten Fold where bedding has been completely obliterated. Thin section shows strong orientation of micas parallel to S_1 (fig. 8. 10).

The features developed during this stage could have formed under the influence of a relatively intense westerly directed stress field which forced schistose material through the gap between the Summas Mountains and the Mitten Fold. Alternatively a rather intense north-easterly-directed stress could have forced the Mitten Fold “ahead” of it, resulting in the warping of the fold axes and the development of parasitic folds and the S_1 and S_{1a} cleavages. In both cases the well-developed S_1 cleavage on Orusewa 1 would have been protected by the Mitten Fold from the relatively intense north-easterly-directed compression of Stage 3. On the southern portion of Delta 400, S_1 has been almost obliterated in minor folds during this later compression.

8.4.2.3 Stage 3

During this, the last stage of the F_2 phase, structures in the vicinity of the eastern flank of the Naauwpoort Ridge became very tightly compressed against it. The minor folds on Delta 400 were compressed into isoclinal structures and throughout the whole area flexure folding gave way to shear folding which culminated in the development of a penetrative regional cleavage, S_2, in the Kuiseb schist [fig. 8. 11 (a) and (b)]. East of the Naauwpoort Ridge, S_2 has an average strike of 16° and steep westerly dip of 85° [figs 8.2 (a) and (b)]. Along most fold axes it becomes axial planar in character [figs 8. 2 (b), 8. 3 (a) and 8.12] and in case of the Okapereka Syncline (fig. 8.4, S_2 measurements from west flank of Okotjize Fold) and Okongwe Fold, it is axial planar throughout. On Orusewa 1, S_1 is dominant and S_2 occurs mainly as well-developed crenulations on S_1 surfaces (fig. 8.10).

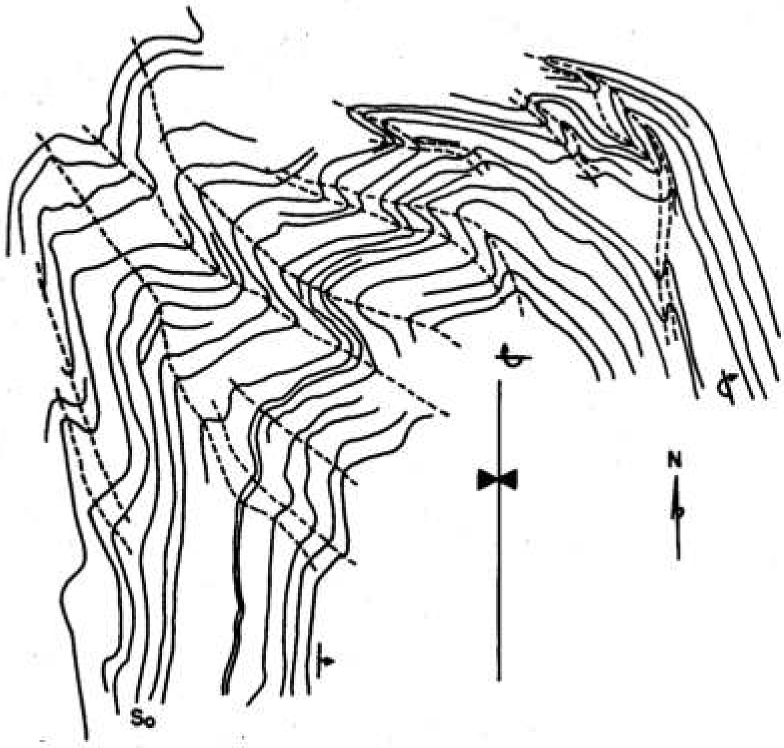
West of the Naauwpoort Ridge, S_2 is largely axial planar in character. The only exception to this is in the minor folds on Nooitgedacht 399 and Delta 400 where S_2 dips steeply to the north-east (figs 8 .7 and 8. 11). Over most of the area S_2 has an inclination of between 60° and 70° to the south-west reflecting the strike and asymmetry of the structures (fig. 8. 13). In the aureole rocks of the Salem granite the original fissility of the schist is partially lost and S_2 acquires a vertical attitude. On Karstenville 405 both the strike and dip of S_2 change and follow the form of the nearby flank of the Mitten Fold.

Thin section shows that metamorphic recrystallisation took place during this stage as all micaceous minerals are orientated parallel to S_2. The only exception is in the Orusewa area where biotite lies parallel to S_1 and S_{1a} cleavages.

Various mechanisms of folding are displayed by different major structures. Formation of similar folds was accompanied by the development of cleavage and thickening of beds in axial regions (all F_2 structures and the F_1 noses of the Okotjize and Okongwe Folds); concentric folds (F_1 noses of the Mitten Fold) display neither of these features. Disharmonic folding is well displayed by the quartzites of the Okenyenya Syncline where many minor folds are characteristic of one particular quartzite layer only. A large amount of thickening has taken place in the axial regions of many of these folds, while the limbs have been so drawn-out that in places beds taper and disappear completely.

The intrusion of the Salem granite postdates this stage of the F_2 phase.

In the outcrops of Swakop rocks on the extreme western edge of the area, overturned structures with both easterly and westerly dipping axial planes are present. A prominent westerly dipping cleavage is developed which is axial planar in structures that are overturned to the east. In the vicinity of the Salem granite this cleavage has been all but obliterated by thermal metamorphism. Its pre-Salem gran-



Trace of major fold axis/Spoor van hoofplooias

So Bedding/Gelaagdheid

Trace of axial planes of parasitic folds/
Spoor van asvlakke van parasitiese plooie

Scale approx.
Skaal ongeveer 1:36 000

Fig. 8.8 — Sketch from an aerial photograph of parasitic folds in the northern closure of the Okapereka Syncline. The axis of the major structure is overturned in this region and plunges very steeply northwards.
Skets van 'n lugfoto van parasitiese plooie in die noordelike geslote struktuur van die Okapereka-sinklien. Die as van die hoofstruktuur is omgekeer in hierdie omgewing en duik baie steil in 'n noordelike rigting.

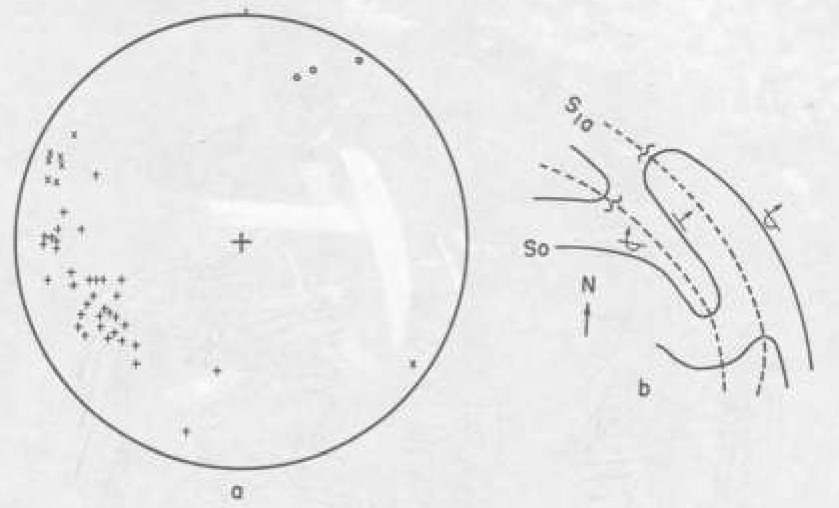


Fig. 8.9 – (a) Structural data from closures of parasitic folds at the northern limit of the Okapereka Syncline. (b) Sketch of parasitic folds.
(a) Struktuurgegewens van geslote parasitiese plooie op die noordelike grens van die Okapereka-sinklien. (b) Skets van parasitiese plooie.

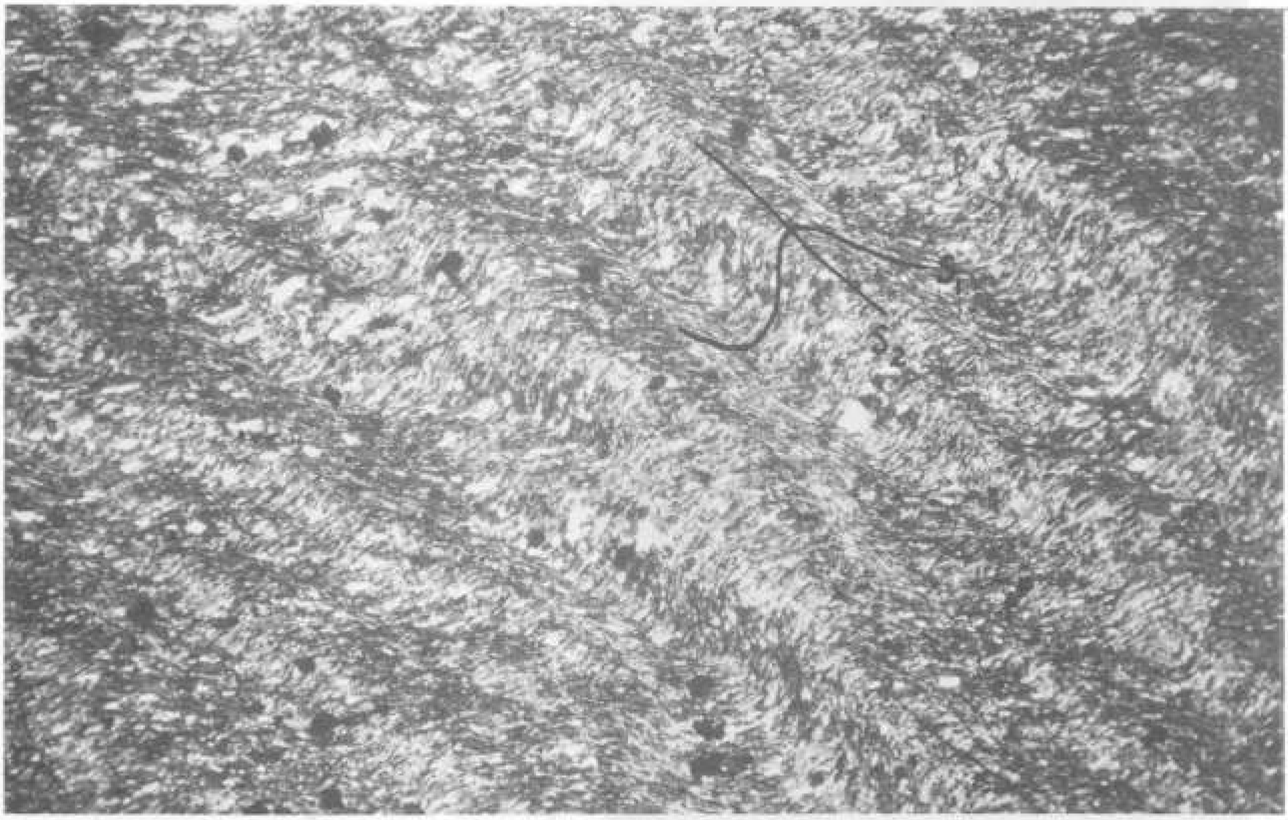


Fig. 8.10—Photomicrograph showing growth of micas parallel to the plane of the s_1 cleavage. The axial plane of the crenulations is parallel to s_2 (×18).
Mikrofoto wat die groei van mika parallel met die vlak van die s_1-kliewing toon. Die asvlak van die fynkartelings is parallel met s_2 (×18).

Fig. 8.11 (a)—Highly penetrative axial planar s_2 cleavage developed in the schist on Delta 400.
Sterk deurdringende s_2-asvlakkliewing soos ontwikkel in skis op Delta 400.

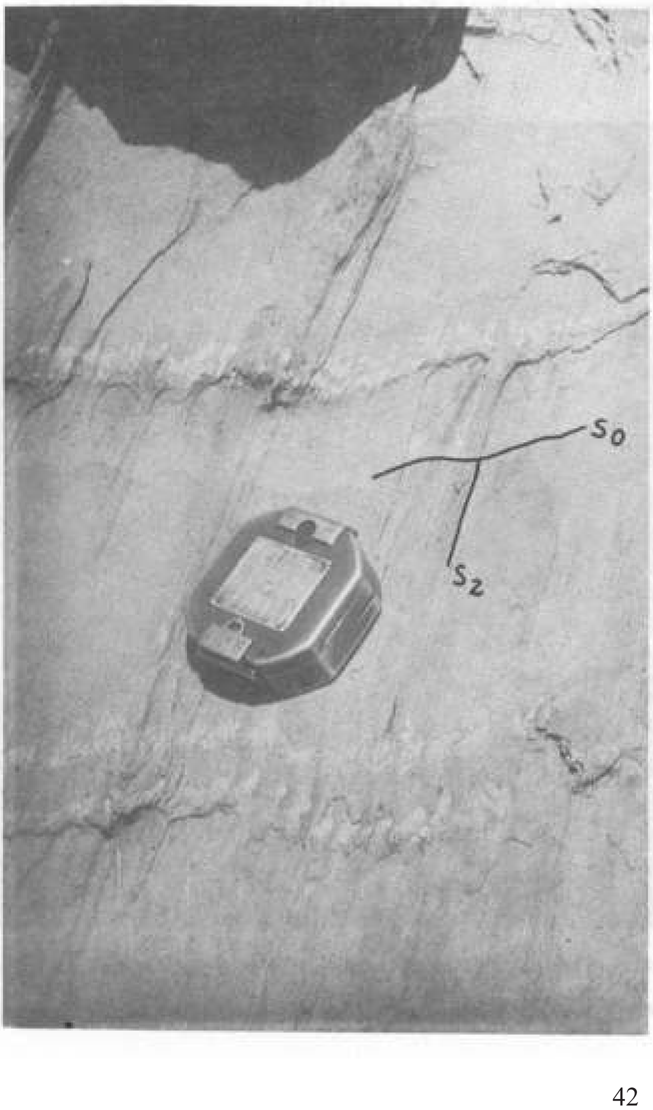


Fig. 8.11 (b)—Shear folding related to the development of s_2, in the Ugab River near the axis of the Okapereka Syncline.
Skuifskeurplooiing verwant aan die ontwikkeling van s_2, in die Ugabrivier naby die as van die Okaperekasinklien.

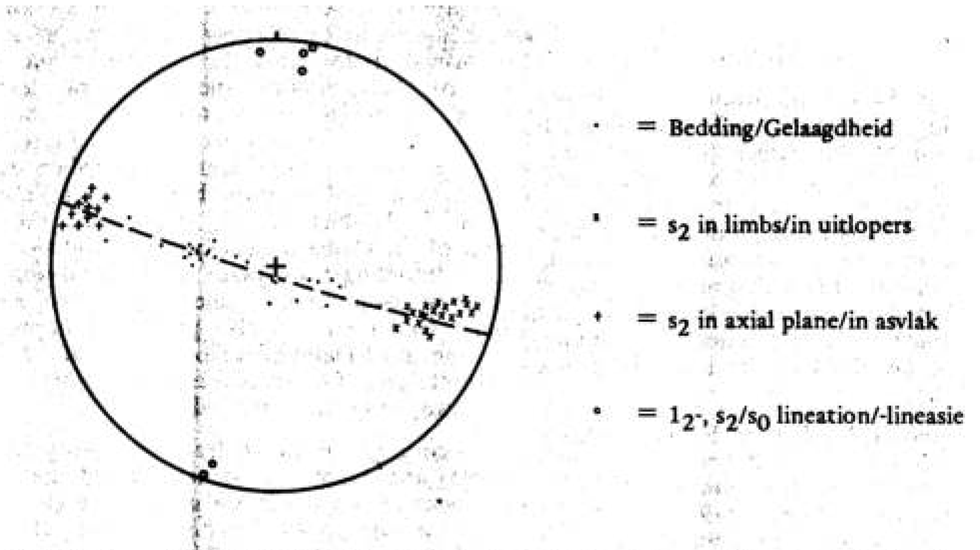


Fig. 8.12 — **Structural data from Ondundo Anticline 5 km northwest of Okotjandjoura.**
Struktuurgegewens van die Ondundo-antiklien 5 km noordwes van Okotjandjoura.

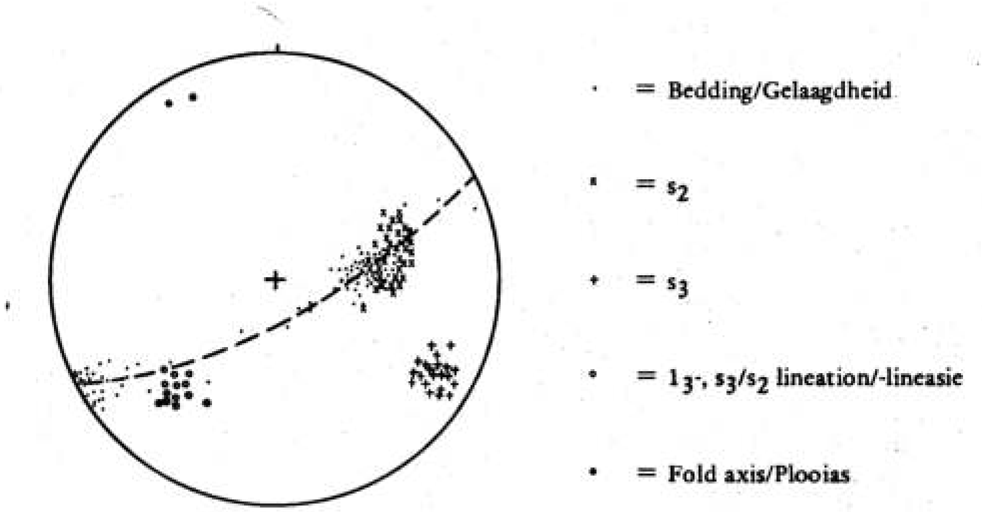


Fig. 8.13 — **Structural data from the Dagbreek Syncline.**
Struktuurgegewens van die Dagbreeksinklien.

ite age and westerly dip therefore suggest an F_2 association. West of the present area the cleavage gradually attains a vertical attitude and then near Gai-As, approximately 50 km due west of the Misoes beacon, it acquires an easterly dip (Hodgson 1972).

8.4.2.4 *Tectonic slide in the Okotjize Fold*

Ramsay (1967, p. 546) demonstrates how, during interference folding, a tectonic slide can develop in the axial region of the earlier fold. The slide parallels the curve of the refolded axial plane and beds on the convex side of the slide are thrown down. Fleuty (1964) gives the following definition: "A slide is a fault formed in close connection with folding, which is broadly conformable with a major geometric feature (either fold limb or axial surface) of the structure, and which is accompanied by thinning and/or excision of members of the rock succession affected by folding.".

In the tightly refolded Okotjize Fold a tectonic slide occurs very close to where the refolded F_1 axis should be at its point of maximum curvature. It differs from that shown by Ramsay (1967, figs 10-29, p. 547) in that it does not extend the full length of the F_2 axis, and also in that there has been a considerable displacement in the axial region. As far as can be ascertained from the poor exposures, the slide dips 65° N where it is intersected by the F_2 axis. There is such a large component of vertical movement on the convex side of the slide that rocks of the U gab Subgroup are no longer exposed (fig. 8. 14). Transverse faults, more or less symmetrically situated on either side of the F_2 axis, sharply truncate the Okotjize and Chuos Formations and the Karibib Formation. It would appear that the combined effect of movement on the slide and the transverse faults was responsible for the sharp truncation of the various horizons, the displacement of the whole of the Ugab Subgroup and the juxtaposition of the Karibib Formation and the slide. The transverse faults may in part be tension features, thus accounting for the relatively short length of the slide.

8.4.3 F_3 structures

The only feature recognised with certainty as being an F_3 structure is a weakly developed east-north-east-orientated subvertical cleavage (S_3) in the schist on Dagbreek 495 and neighbouring farms (fig. 8.13). It forms fine crenulations and a lineation on S_2 surfaces. Near the Salem granite where the earlier S_2 cleavage has been partially obscured by thermal metamorphism, S_3 imparts a new fissility indicating that it postdates the granite.

In this area S_3 is not accompanied by folding but farther to the north-west it attains a north-south orientation, becomes highly penetrative and is associated with folding (Frets 1969, p. 204).

8.4.4 F_4 structures

The final phase of deformation is represented by kink folds (figs 8. 15 and 8 . 16) which developed in the earlier S_2 cleavage in brittle response to a north-north-east-orientated compression (Turner and Weiss 1963, p. 476). These occur on the eastern flanks of the Okotjize and Okongwe Folds and the Okenyenya Syncline. Usually only one set of kink folds is present but rare conjugate sets are developed.

8.5 CONTRASTED RESPONSE OF SWAKOP AND PRE-SWAKOP MEMBERS OF THE STRATIGRAPHIC SEQUENCE TO FOLDING

From a glance at the map of the area it is immediately apparent that the rocks of the Swakop Group (the highest in the succession) are the most strongly deformed. Below this the folding in the relatively massive Naauwpoort volcanics is far less intense while the gneiss just to the north of the Summas Mountains has been least affected. Frets (1969, p. 205) noted that the Kamanjab Inlier apparently acted as a rigid resistant block during deformation. Similarly Hälbich (1970), working on the southern edge of the Damara geosyncline, found that although local infolding took place under conditions of high tectonic overpressure, shearing of basement and basal Damara rocks also played an important part 1n the post-Damara deformation of that region. The intensity of shearing decreases rapidly southwards, i.e. away from the basin edge.

In contrast, in the centre of the geosyncline Smith (1965) and Jacob (1974) have found that structures in rocks of the Nosib Group and basement (mainly acidic in composition) reflect those in the overlying Swakop metasediments. Thus in the relatively cold marginal regions of the geosyncline the massive granitic pre-Damara rocks have proved remarkably resistant to deformation while in the axial regions very high temperatures (Smith 1965) rendered these rocks far more plastic and more susceptible to deformation.

8.6 THRUST FAULTING OF POSSIBLE LATE OROGENIC AGE

A thrust fault with a north-easterly trend and 25° dip to the south-east occurs just north of Otjozondjou village. The thrust is located mainly within the Kuiseb schist but at its north-eastern extremity it forms the boundary between Salem granite and Kuiseb schist. Vertical ring dykes associated with the post-Karoo Otjohorongo Granite have been displaced by the thrust and on a small subsidiary thrust west of Otjozondjou, Kuiseb schist has overriden rocks of the Omingonde Formation.

Pre-Karoo formation of the thrust is suggested by considering the approximate 0,5-km displacement of the post-Karoo ring dykes in relation to the contrasting metamorphic grades of the Damara rocks juxtaposed across the thrust. Good outcrops west of Otjozondjou show that high-grade migmatitic biotite schist which borders the Salem Suite has overridden a chlorite-muscovite schist. The biotite schist is an injection migmatite (i.e. injected granitic veins) farthest from the Salem granite but it grades into an *in situ cum* injection migmatite with clear leucosomes and melanosomes showing various degrees of partial melting closer to the granite. Furthermore, the whole of the adjacent marble is coarsely crystalline indicating that the metamorphic grade of the migmatitic biotite schist and the marble are due not to thermal metamorphism caused by the granite, but to regional metamorphism. Juxtaposition of such high- and low-grade metamorphic rocks across the thrust would have required a displacement well in excess of 0,5 km.

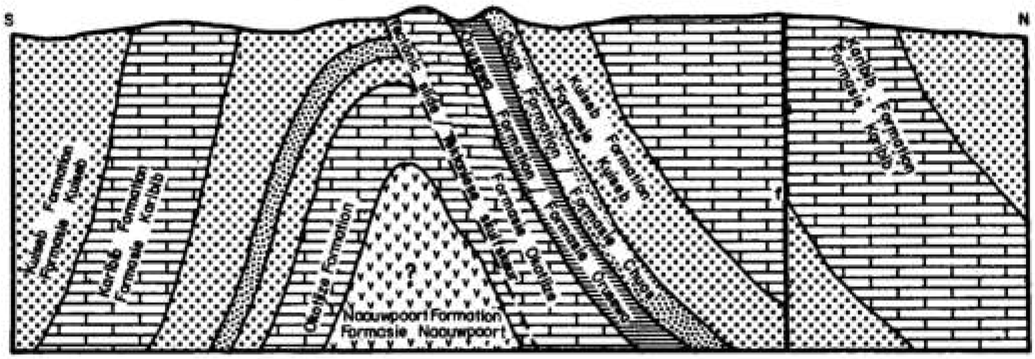
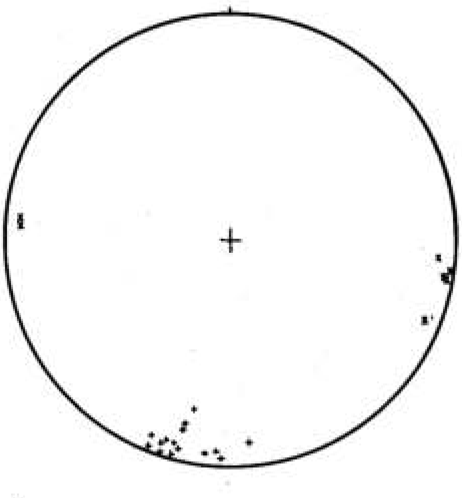


Fig. 8.14 — Diagrammatic section along the F_2 axis of the Okotjize Fold showing the position of the tectonic slide. Similar folding has caused abnormal thickening in the Orusewa, Chuos and Karibib Formations and the lowermost portion of the Kuiseb Formation.
Diagrammatiese profiel langs die F_2-as van die Okotjizeplooi wat die posisie van die tektoniese skuifskeur toon. Soortgelyke plooiing het tot abnormale verdikking van die Formasie Orusewa, Chuos en Karibib en die onderste deel van die Formasie Kuiseb gelei.



× s_2

\+ s_4, axial plane of kink folds/asvlak van kinkelplooie

Fig. 8.16 — Structural data for F_4 kink folds, 2 km east of Okenyenya.
Struktuurgegewens vir F_4-kinkelplooie, 2 km oos van Okenyenya.

Fig. 8.15—Kink folds in the s_2 cleavage, 2 km east of Okenyenya.
Kinkelplooie in die s_2-kliewing, 2 km oos van Okenyenya.

Clearly, most of this movement predates intrusion of the Otjohorongo Granite. It could have been immediately pre-Karoo or intra-Karoo, associated, possibly, with syn-sedimentary faulting in the coastal regions. However, brecciation of the so-called Red Band along the southern margin of the Damara orogen indicates a very late phase of deformation in the Damara belt which appears to postdate the youngest fabric in that region. Initiation of the thrust near Otjozondjou could belong to this phase of deformation.

The thrust is probably complementary to the northwesterly dipping Waterberg Thrust which may, thus, also be a rejuvenated late-orogenic feature.

9. POST-DAMARA METAMORPHISM

The peak of the regional metamorphism was reached during or just after the final phase of F_2 shear folding. Grain-size changes and characteristic mineral assemblages show that the grade increased from north to south (fig. 9.1) and that metamorphism culminated in anatexis and the formation of the Salem Suite and Sorris-Sorris Granite. Post-tectonic intrusion of the Salem granite into cooler zones produced a conspicuous thermal aureole which stretches from south of Okenyenya to the northwestern corner of the area and along the contact between granite and schist in the west.

9.1 METAMORPHISM OF NAAUWPOORT FORMATION

During post-Damara metamorphism, which was most intense in the south, the Naauwpoort rocks became devitrified, recrystallised and finally remobilised.

All the volcanics in the north are devitrified but still retain their igneous appearance. Towards the south there is a gradual increase in grain size and the rocks become arkose-like in appearance. In the regions of high-grade metamorphism concordant secretion pegmatites provide evidence of incipient melting. More complete melting led to the formation of the Sorris-Sorris Granite.

Aspects of the rocks which only underwent devitrification have already been described (see section on petrography). In the Ais Dome and all but the western margin of the Mitten Fold, recrystallisation produced rocks with a uniform light-reddish colour and monotonous arkose-like appearance which bear no resemblance to felsitic or glassy-textured volcanic rocks. The very fine grain typical of specimens from the northern portion of the Mitten Fold gradually increases towards the south until all the individual minerals become distinguishable. Granoblastic quartz and fresh cross-hatched microcline perthite are major constituents in all specimens (fig. 4.8). They are accompanied by minor to accessory amounts of fresh or only slightly saussuritised plagioclase ($An_{0\text{-}18}$) and muscovite and accessory biotite, ore, tourmaline, zircon and secondary chlorite. This association holds for all the recrystallised Naauwpoort rocks despite small-scale redistribution of the feldspars into separate bands consisting of potash feldspars and quartz only or plagioclase and quartz only. There has also been very late-stage growth of randomly orientated poikiloblastic muscovite and plagioclase in certain samples from the Ais Dome and southern margin of the Mitten Fold.

Because of the appearance of these rocks it is not surprising that they were originally considered to be Nosib Group arkoses (Geological Map of South West Africa, 1963) and it is worthwhile at this stage to mention characteristics which enable them to be distinguished from arkoses: (I) Layers of unaltered pyroclastic rocks in the western portion of the Mitten Fold can be traced into areas where they became completely recrystallised. (2) The rocks lack any features that resemble typical sedimentary bedding and are generally massive on fresh surfaces though they are slightly foliated in the Ais. Dome. Flow banding and pyroclastic textures are still visible on weathered surfaces in the Mitten Fold up to about I km from the contact with the Salem granite. In the Ais Dome neither of these features is present. (3) Cross-bedding is absent. (4) The grain size is fairly consistent throughout, whereas in an arkose some form of lithological change would be expected. (5) There is no heavy-mineral layering and no pebble inclusions occur. (6) Nearly all the feldspar is fresh. (7) The predominance of microcline over sodic plagioclase reflects the chemistry of the parent rocks. (8) Feldspar content is consistently high throughout the whole area as the modes in table 9. I indicate. (9) Thin sections show characteristic granoblastic mosaic texture in which rounded quartz grains are often completely or partially enclosed by xenoblastic microcline grains. Many of the latter have irregular shapes where they partially enclose several quartz grains. Idioblastic and subidioblastic grains are entirely lacking (fig. 4.8).

Table 9.1 MODES OF RECRYSTALLISED NAAUWPOORT FORMATION ROCKS ILLUSTRATING HIGH PROPORTION OF FELDSPAR

Sample No.	Quartz	Micro-cline	Sodic plagio-clase	Musco-vite	Biotite and chlorite	Ore
RM 26...	29,0	47,0	20,0	3,0	0,4	1,0
RM 108..	34,0	56,0	4,0	1,0	3,0	2,0

RM 26—Southern margin of Mitten Fold.
RM 108—Ais Dome.

Evidence of incipient melting is provided on a small scale by granite veinlets and on a larger scale by secretion pegmatites which are mostly concordant with the original igneous layering (indicated by banding or the attitude of the overlying Ugab sediments). These features are very conspicuous in the Ais Dome and along the southern margin of the Mitten Fold. In the latter case thermal metamorphism resulting from the intrusion of the Salem granite has been superimposed on regional metamorphism and has caused the melting. In parts of the Ais Dome even higher temperatures have effected complete remobilisation resulting in the production of the magma from which the Sorris-Sorris Granite crystallised. One particular outcrop shows a complete gradation from reddish arkose-like Naauwpoort metavolcanic rocks through an intermediate zone into massive red Sorris-Sorris Granite. The intermediate zone consists of medium-grained to slightly pegmatitic granite which is riddled with rounded disintegrating metavolcanic "xenoliths". The large volume of Sorris-Sorris Granite intrusive into the Salem granite must have come from levels deeper than those now exposed in the Ais Dome because in this structure only small portions of the Naauwpoort metavolcanic rocks have been completely remobilised.

9.1.1 Characteristics of the pegmatites

The pegmatites range in thickness from 10 cm to 7 m and though mineralogically quite straightforward, have an extremely variable internal structure. The simplest and most common are homogeneous, with quartz and pink microcline perthite (3 mm to 3 cm in diameter) as the main constituents. Muscovite (3 mm to 25 mm) is generally present in very minor or accessory amounts and minor white plagioclase (3 mm to 25 mm) and accessory biotite may also occur. The homogeneous pegmatites are generally structureless but along the margins of a few, perthite pheno-crysts and plumose quartz/muscovite intergrowths are orientated perpendicular to the contact. Ill-defined finger-grained border zones are developed in places.

The homogeneous pegmatites grade into fairly simple zoned pegmatites (relatively thin) which in their turn can become relatively complex .when banding accompanies zoning (fig. 9.2). However, the detailed study of pegmatites is vast (Cameron *et al.* 1954; Jahns 1955) and not within the scope of this survey.

9.2 METAMORPHISM OF SWAKOP GROUP

9.2.1 The carbonate association

The most obvious effect of the southward increase in metamorphic grade on the carbonate rocks is an increase in grain size. This becomes apparent in the southern margin of the Summas Mountains. Where dolomitic and calcitic marbles have been affected by comparable grades of metamorphism, the latter invariably show the greater amount of recrystallisation. The dolomitic marbles around the Ais Dome are medium grained whereas the calcitic marble of the Karibib Formation in the vicinity of Okombahe village is very coarse grained and contains crystals up to 5 cm in diameter.

9.2.1.1 *Reactions involving magnesium-bearing minerals*

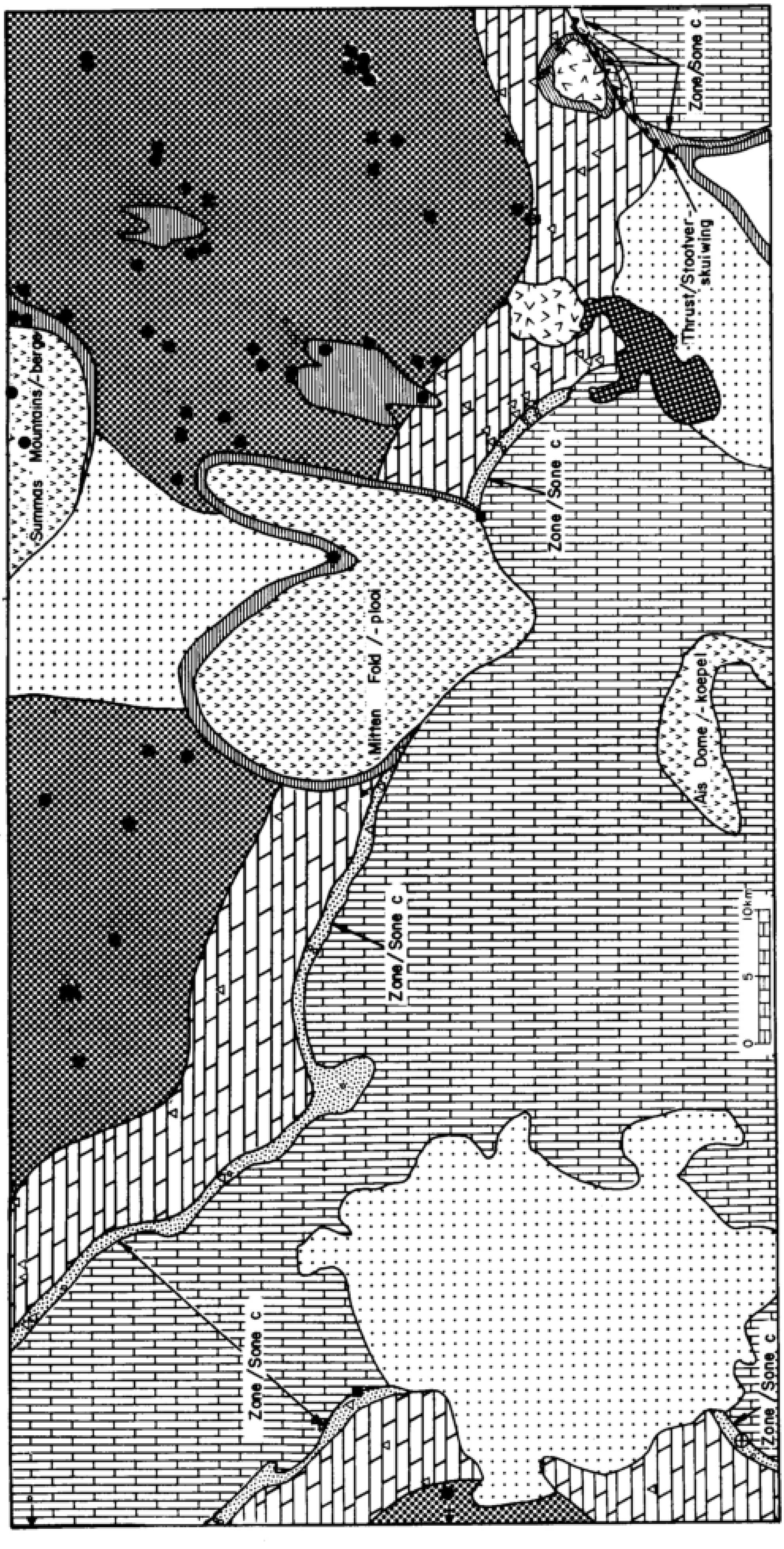
The first signs of a reaction between quartz and dolomite (reaction 1, fig. 9.3) are provided by the appearance of talc in the core of the Okotjize Anticline and in the upper layers of the Okotjize Formation in the south-eastern corner of Nooitgedacht 399. The assemblage dolomite-talc-calcite occurs, but in the samples taken the reaction has not quite reached completion, however, as a little quartz is also present.

The next stage is the formation of tremolite which either replaces talc completely or forms directly through the reaction between quartz and dolomite (reactions 2, 3, 4 and 5, fig. 9.3).

Small amounts of colourless tremolite are found in certain layers underlying the talcose beds on Nooitgedacht 399 but it becomes very abundant farther south on Karstenville 405 where it is mainly in the form of fine needles. However, porphyroblasts up to 5 cm long are not uncommon.

Around the Ais Dome only very little colourless tremolite was found, but there is a great deal of it which is very coarse grained and green in hand specimen but generally colourless or only very faintly pleochroic in thin section. The tremolite is disseminated through most samples, but also makes up more than 80 per cent of several rather spectacular layers.

Where bulk compositions are suitable, tremolite will react further as the metamorphic grade increases and diopside will form (reactions 6, 7 and 8, fig. 9.3; Metz 1967). Where there is a deficiency of silica, forsterite can also form (reactions 11, 12, 13, 14 and 15, fig. 9.3).


Summas Mountains/-berge
Mitten Fold/-plooi
Zone/Sone c
Zone/Sone c
Zone/Sone c
Zone/Sone c
Zone/Sone c
Zone/Sone c
Thrust/Stootver-skuiwing
Ais Dome/-koepel
0 5 10km

LEGEND/LEGENDE

- Superficial deposits/Oppervlakafsettings
- Post-Karoo intrusions/Na-Karoo-intrusies
- Karoo Sequence/Opeenvolging Karoo
- Salem Suite/Suite Salem
- Kuiseb schist/Kuisebskis
- Ugab carbonate rocks/Ugab-karbonaatgesteentes
- Naauwpoort Formation/Formasie Naauwpoort

METAMORPHIC ZONES/METAMORFE SONES

● Zone a – Muscovite + Mg-chlorite + quartz / Sone a – Muskoviet + Mg-chloriet + kwarts

▵ Zone b – Biotite + quartz ± muscovite ± clinochlore / Sone b – Biotiet + kwarts ± muskoviet ± klinochloor

▾ – Biotite + quartz + andalusite + muscovite/ – Biotiet + kwarts + andalusiet + muskoviet

• Zone c – Biotite + cordierite + quartz ± muscovite ± potash feldspar/ Sone c – Biotiet + cordieriet + kwarts ± muskoviet ± kaliveldspaat

■ – Sillimanite/Sillimaniet

⊕ – Cordierite + biotite + quartz + potash feldspar + muscovite ± almandine/ – Cordieriet + biotiet + kwarts + kaliveldspaat + muskoviet ± almandien

– Otjohorongo granite aureole, fine-grained muscovite + quartz ± biotite/ Otjohorongograniet-oureool, fynkorrelrige muskoviet + kwarts ± biotiet

NB. Zone c more extensive; two mineral associations in Zone a; a number of new data points in all zones.
Sone c meer uitgebreid; twee mineraalassosiasies in Zone a; 'n aantal nuwe datapunte in alle sones.

Fig. 9.1 – Metamorphic facies series of Kuiseb Formation schist. Symbols indicate sample localities.
Metamorfe fasiesreeks van skis van die Formasie Kuiseb. Simbole dui monsterlokaliteite aan.

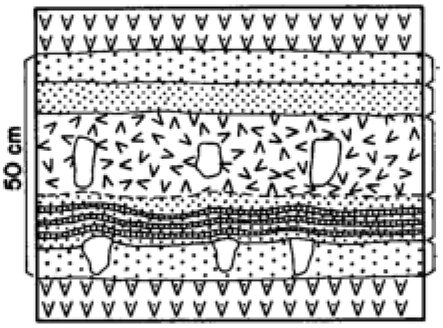


Fig. 9.2 — Illustration of the zones in a subhorizontal complex pegmatite from the southern margin of the Mitten Fold. Minerals listed in order of abundance:—

Border Zone: perthite—quartz—plagioclase—muscovite. Perthite phenocrysts in lower border zone penetrate lower wall zone. Grain size 5—25 mm.

Wall Zone: sugary albite—quartz—muscovite. Three thin, very persistent quartz—muscovite bands in lower wall zone. Muscovite in these bands is perpendicular to contacts. Bands are humped over the perthite phenocrysts which penetrate from the lower border zone. Grain size 2 mm.

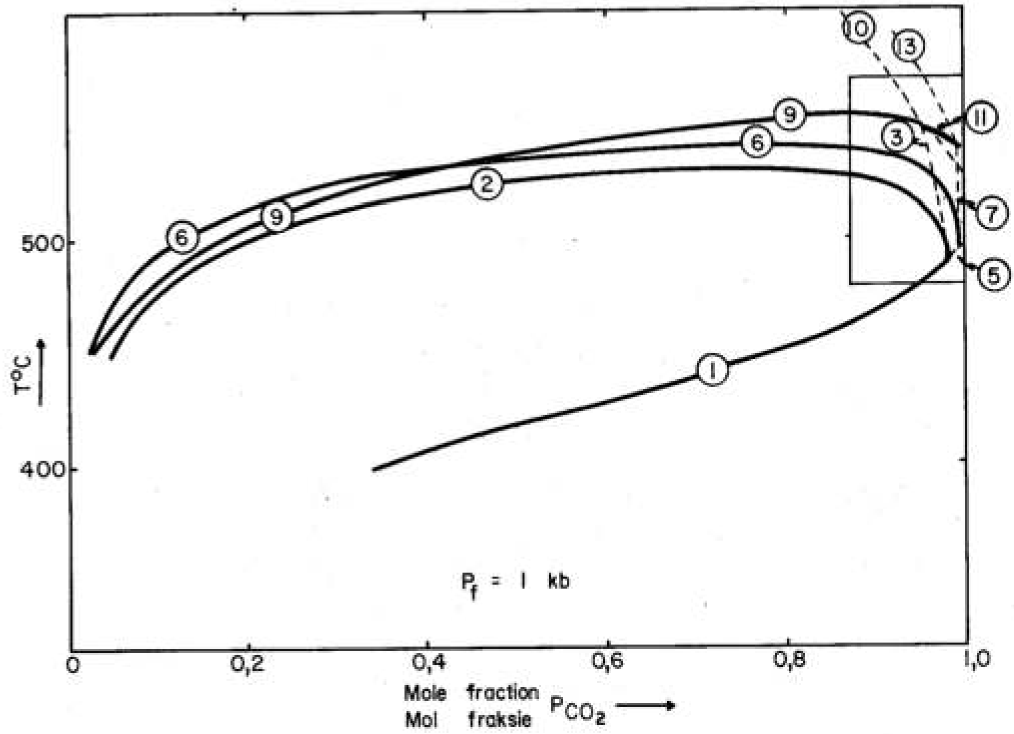
Core: perthite—quartz—muscovite. Large perthite phenocrysts in lower two-thirds are perpendicular to contact. Very fine-grained muscovite concentrated on the contact between core and lower wall zone. Grain size 1—15 cm.

Illustrasie van die sones in 'n subhorisontale komplekse pegmatiet aan die suidelike rand van die Mittenplooi. Minerale word in volgorde van volopheid aangedui:—

Grenssone: pertiet—kwarts—plagioklaas—muskoviet. Pertiet-eerstelinge in onderste grenssone groei tot in onderste wandsone. Korrelgrootte 5—25 mm.

Wandsone: albiet met suikertekstuur—kwarts—muskoviet. Drie dun volgehoue aaneenlopende kwarts—muskovietbande in onderste wandsone. Muskoviet in hierdie bande is loodreg op die kontakte. Bande buig oor die pertiet-eerstelinge wat vanaf die onderste grenssone gegroei het. Korrelgrootte 2 mm.

Kern: pertiet—kwarts—muskoviet. Groot pertiet-eerstelinge in onderste twee-derdes lê loodreg op kontak. Baie fynkorrelrige muskoviet is op die kontak tussen die kern en onderste wandsone gekonsentreer. Korrelgrootte 1—15 cm.



REACTION/REAKSIE

		No./Nr.
3Dol + 4Qtz + $1H_2O$	1Talc + 3Cc + $3CO_2$	(1)
5Talc + 6Cc + 4Qtz	3Trem + $6CO_2$ + $1H_2O$	(2)
2Talc + 3Cc	1Trem + 1Dol + $1CO_2$ + $1H_2O$	(3)
5Dol + 8Qtz + $1H_2O$	1Trem + 3Cc + $7CO_2$	(4)
2Dol + 1Talc + 4Qtz	1Trem + $4CO_2$	(5)
1Trem + 3Cc + 2Qtz	5Diop + $3CO_2$ + $1H_2O$	(6)
1Trem + 3Cc	1Dol + 4Diop + $1CO_2$ + $1H_2O$	(7)
1Dol + 2Qtz	1Diop + $2CO_2$	(8)
1Talc + 5Dol	4Fo + 5Cc + $5CO_2$ + $1H_2O$	(9)
11Talc + 10Cc	5Trem + 4Fo + $10CO_2$ + $6H_2O$	(10)
1Trem + 11Dol	8Fo + 13Cc + $9CO_2$ + $1H_2O$	(11)
13Talc + 10Dol	5Trem + 12Fo + $20CO_2$ + $8H_2O$	(12)
3Trem + 5Cc	11Diop + 2Fo + $5CO_2$ + $3H_2O$	(13)
1Diop + 3Dol	2Fo + 4Cc + $2CO_2$	(14)
4Trem + 5Dol	13Diop + 6Fo + $10CO_2$ + $4H_2O$	(15)

Fig. 9.3 – Isobaric T-P_{CO_2} diagram of phase equilibria in metamorphosed siliceous dolomites at a total fluid pressure of 1 kb, after Metz and Trommsdorff (1968). Solid curves have been experimentally determined, dashed curves are theoretical and based only on calculations of equilibria.
Isobariese T-D_{CO_2}-diagram van fase-ewewigte in gemetamorfoseerde silikabevattende dolomiete by 'n totale vloeistofdruk van 1 kb, volgens Metz en Trommsdorff (1968). Soliede kurwes is eksperimenteel bepaal, stippelkurwes is teoreties en slegs op berekeninge van ewewigte gebaseer.

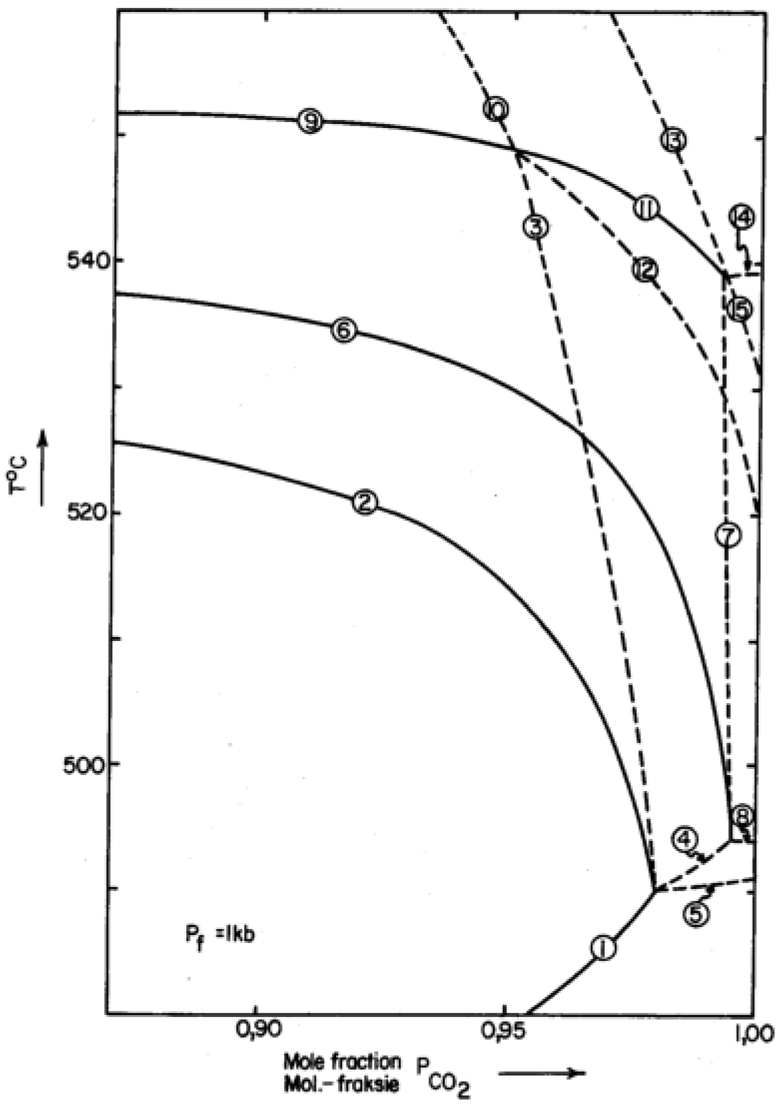


Fig. 9.4 — Enlarged sector of figure 9.3.
Vergrote sektor van figuur 9.3.

Monticellite can form by reaction between diopside and forsterite (Turner 1968, p. 135).

$2Cc+ 1Diop+ 1Fo \leftrightarrow 3Mc+2CO_2$.

On Biesiespoort 408 diopside and forsterite appear in the Okotjize Formation approximately 1 km from the Salem granite. Samples containing monticellite in addition to diopside and forsterite have been collected 100 m from the granite on Leeushoek 411. Farther south around the Ais Dome diopside is abundant but forsterite and monticellite are rare. On the western edge of the area diopside only occurs in one thin band in the dolomite on Uitkoms 525 within 200 m of the granite.

Calc-silicate minerals are not common in the dolo¬mite-poor Karibib Formation near Okombahe village. Diopside is the only Mg silicate that has been found and it is limited to certain layers where it is sparsely disseminated. In one particular sample from this area it would appear as if the reaction $1Dol+2Qtz \leftrightarrow 1Diop+2CO_2$ (reaction 8, fig. 9.4) had taken place. A crosscutting granite veinlet which intruded the marble during metamorphism is now represented only by a vein of microcline, quartz from the granite having reacted with dolomite to form diopside. Plagioclase reacted with calcite to give scapolite. The diopside and scapolite are concentrated along the margin of the microcline vein.

The diopside, forsterite and monticellite are all medium to fine grained and the last two minerals are either partially or completely altered to serpentine. The refractive indices of diopside, given in table 9.2, indicate a fairly variable Fe content. The diopside containing the greatest amount of Fe is accompanied by a rather iron-rich vesuvianite. Diopside in RM 116 (a very thin layer of calc-silicate rock interbedded in schist on Leeushoek 411) is accompanied by small amounts of biotite, which would indicate a greater amount of Fe in this whole sample.

Table 9.2 REFRACTIVE INDICES OF DIOPSIDE FROM SELECTED SAMPLES OF SKARN

	SW margin Mitten Fold			Ais Dome		
Sample no.	RM 116	RM 301	RM 55	RM 61	RM 63	RM 146
n_z	1,711	1,702	1,698	1,700	1,706	1,716
n_y	1,687	1,679	1,675	—	1,684	—
n_x	1,679	1,672	1,670	1,670	1,677	1,687
Mg/(Mg+Fe) per cent	78	91	95	94	85	70

Accuracy ± 0,001. Proportion Mg after Hess (1949).

The 2V values of forsterite and monticellite are given in table 9.3. Values for forsterite indicate more than 96 per cent Fo (Deer, Howie and Zussman 1963). The 2V of monticellite indicates that it is also rich in Mg (Tröger 1959, part 1).

9.2.1.2 *Quartz-calcite reactions*

Quartz-calcite associations occur throughout the area and are even fairly common in the high-grade metamorphic zones of the Ais Dome and in the vicinity of Okombahe village. The reaction $Cc+Qtz \leftrightarrow Wo+CO_2$ has only taken place in the extreme west on Uitkoms 525 within 200 m of the Salem granite. Two sinuous bands of wollastonite rock occur which vary from 10 cm to 1 m in thickness. The wollastonite, which forms a compact mass of white needles, is accompanied by variable amounts of calcite and a little diopside.

Table 9.3 2V ANGLES OF FORSTERITE AND MONTICELLITE IN DOLOMITIC MARBLES

	SW margin Mitten Fold	Ais Dome
Sample no.	RM 828	RM 52
Forsterite 2Vz..............	83 – 85	81 – 85
Monticellite 2Vx..............	88,5	84 – 88

9.2.1.3 *Reactions involving aluminium-bearing skarn minerals*

The first aluminium-bearing silicate to appear in the marbles is a colourless Mg-rich chlorite which forms small subhedral porphyroblasts in the lenses of white dolomite which occur at the top of the Orusewa Formation on the southern margin of the Summas Mountains. The colour, length-fast orientation and anomalous brownish-green birefringence (approximately 0,01) of the chlorite indicate its Mg-rich character (Albee 1962). It is probable that the rock originally contained small amounts of a clay mineral with which the dolomite was able to react to form chlorite.

Around the Ais Dome the most abundant skarn mineral is scapolite. Besides being a fine- to coarse-grained constituent of nearly every sample, it also forms between 80 and 90 per cent of two layers which vary from 10 to 30 m in thickness. In the latter, slender crystals of scapolite up to 1 m in length and 2 cm wide occur in large radiating clusters (fig. 9.5).

Only small amounts of scapolite occur in the rest of the area. In the west on Uitkoms 525 scapolite is found associated with diopside. On the southwestern margin of the Mitten Fold it is a poikiloblastic constituent of thin lenses of calc-silicate rock that are interbedded in the Khomas schist (table 9.4, RM 116). It also occurs in the Karibib Formation in the vicinity of the Okombahe village where it forms isolated crystals. The formation of scapolite in this area by reaction between calcite in the marble and plagioclase of an intrusive granite veinlet has already been mentioned. The low birefringence of this scapolite is indicative of a sodic composition.

The refractive indices and birefringence of selected scapolite samples are given in table 9.4. The original reason for carrying out refractive-index determination on scapolite was to obtain an estimate, firstly of the soda content, and secondly, of the amount of chlorine present. Scapolite is very abundant in the layered skarn rocks of the Ais Dome and this suggests that fairly large quantities of Cl may either have been present in the original sediments, or may have been released from the underlying Naauwpoort rocks during metamorphism.

Fig. 9.5—Radiating clusters of long slender scapolite crystals in layered skarn. Dark minerals are diopside and tremolite. Northern margin, Ais Dome.
Uitstralende bondels van lang dun skapolietkristalle in gelaagde skarn. Donkerminerale is diopsied en tremoliet. Noordelike rand van die Aiskoepel.

Table 9.4 REFRACTIVE INDICES AND BIREFRINGENCE OF SCAPOLITE FROM SELECTED SAMPLES OF SKARN

	SW margin Mitten Fold		Various layers in the Ugab Subgroup surrounding the Ais Dome					Uitkoms 525		
Sample no.	RM 116	RM 55	RM 58	RM 59	RM 61	RM 62*	RM 63	RM 356	RM 802	RM 803
$n\omega$	1,569	1,565	1,557	1,561	1,569	1,576	1,582	1,566	1,580	1,581
$n\varepsilon$	1,546	1,546	1,544	1,543	1,546	1,548	1,553	1,545	1,550	1,549
$n\omega - n\varepsilon$	0,023	0,019	0,013	0,017	0,023	0,028	0,029	0,021	0,030	0,032
Me/(Me+Ma) per cent	45	40	31	34	46	53	64	40	61	62
$CO_2/(CO_2+Cl)$ per cent	75	64	25	62	77	85	80	73	68	92

Me—meionite.
Ma—marialite.
Proportion meionite after Shaw (1960), proportion CO_2 after Tröger (1959, part 1).
*—pure scapolite layer.

The end members of the scapolite group, meionite, represented by the formula $(An)_3CaCo_3$, and marialite, $(Ab)_3NaCl$, form a solid-solution series. Ideally the amount of Cl increases as Na increases and Shaw (1960) has shown that there is a linear relationship between birefringence and mean refractive index on the one hand and composition on the other. An increase in Cl should therefore be proportional to the increase in Na. All but one of the samples (RM 58) show an excess of carbonate and a deficiency of Cl in relation to Na. The low Cl content of these samples is also indicated by the fact that the values obtained for birefringence (RM 58 excluded) are 20 per cent higher than the values given by Shaw (1960) for corresponding proportions of marialite and meionite. Shaw (1960, p. 254) attributes abnormally high values for birefringence to substitutions of OH-, HSO_4- and CO_3^{2-} for Cl- in marialite. There is no systematic change in the Cl content of scapolite in the sequence from the Ais Dome area so it is probable that there was no significant release of the element from the Naauwpoort rocks during metamorphism. A high marialite content might suggest the former presence of evaporitic minerals (Kwak 1977). It would seem that except for the layer represented by sample RM 58, the Damara carbonate sequences contained very little NaCl, although some sulphate might have been present as suggested by the high birefringence of the scapolite.

The observation by Haughton (1971) that plagioclase is more calcic than co-existing scapolite when both have a high content of Ca, and vice versa when both are sodic, is borne out by associations from the present area.

Hietanen (1967) found that the Ca content of scapolite increased as the grade of metamorphism increased. All the samples from the present area show a very variable meionite content and it would seem that local bulk composition is very important in determining the eventual composition of the scapolite that forms.

Plagioclase, present in a few samples from the Ais Dome and one from the Mitten Fold, has two origins. Where it was an original detrital component of the rock it is fairly well zoned and has a composition that varies from An_{16} to An_{31} but where it is metamorphic in origin it is only slightly zoned and varies from An_{57} to An_{70}. In one sample plagioclase and scapolite form a coarse intergrowth.

Microcline, which is present in a few samples, is a recrystallisation product of potash feldspar present in the original sediment.

Small quantities of colourless phlogopite (n_z= 1,578±0,001) occur 100 m from the granite on Leeushoek 411. Around the Ais Dome only accessory quantities of very light-brown phlogopite were found which are now partially altered to Mg chlorite. There are rare occurrences of a 2- to 3-cm-thick band of pure very coarse-grained Mg-rich biotite (n_z= 1,593±0,001) near the top of the skarn horizons around the Ais Dome and on Rooipoort 414.

Small amounts of garnet with a strong reddish-brown colour occur on the extreme south-western edge of the Ais Dome and in the west on Uitkoms 525. In the former case the garnet forms symplectic intergrowths with quartz and in the latter with scapolite. The approximate refractive index of both samples is 1,81. Although refractive indices alone cannot be used to indicate garnet composition (Rickwood, Mathias and Siebert 1968), the mineral associations suggest that these garnets are rich in andradite and grossular.

Vesuvianite (n>1,73) has been found in fairly large amounts in one sample from the Ais Dome. It is colourless, has a weak anomalous greyish-blue birefringence and is optically positive. The last property is characteristic of a high water content while the refractive index indicates that TiO_2+Fe_2O_3+FeO make up more than 5 per cent by weight (Tröger 1959, part 1).

In a few specimens from the Ais Dome small amounts, of epidote, allanite, clinozoisite and Mg chlorite can be found. The last mineral is in a sample that also contains forsterite and monticellite which seems most unusual. However, the sample is made up mainly of carbonate and has only small proportions of calc-silicate minerals disseminated through it. The chlorite probably formed at an early stage and remained stable within its immediate environment during the continued temperature rise which eventually enabled the other Mg silicates to form.

Sphene is a ubiquitous accessory mineral and a little apatite is present in places.

9.2.2 Pelitic association

Low-grade schist with mineral assemblages typical of the greenschist facies occur over almost the whole area. These give way to higher-grade biotite and cordierite-rich zones which border the Salem granite. Very near the contact between the granite and the schist there is local development of sillimanite and in the south-west almandine occurs.

The main mineral assemblage of the low-grade schist is muscovite+magnesian chlorite+quartz±biotite, which is typical of the greenschist facies (zone a in fig. 9.1). Plagioclase where observed is albitic (An_{0-8}). Epidote is only present in one sample, an impure quartzite from the core of the Ondundo Anticline. The absence of staurolite and the very limited occurrence of andalusite in the higher-grade schist indicate that it is unlikely that muscovite is accompanied by significant amounts of pyrophyllite, if there is any.at all. All schist specimens show good lepidoblastic textures which developed in conjunction with shear folding at the end of the F_2 phase of deformation. The first signs of thermally induced post-tectonic recrystallisation are a spotting by clusters of biotite flakes in certain layers some 12 km north of the contact with the Salem granite.

At a distance of 7 to 8 km from the Salem granite the assemblage biotite+quartz±muscovite±clinochlore develop (zone b in fig. 9.1). The main reaction is the formation of biotite from chlorite and muscovite. The very small quantities of clinochlore indicate only a small excess of Mg, Fe and Al over the amount required by biotite. The width of zone b stays more or less constant.

In zone b the clusters of biotite flakes become more commonplace. A few crystals of biotite and muscovite, slightly larger than average, which have a random orientation are invariably present. Clinochlor is usually porphyroblastic to poikiloblastic and generally lacks orientation. Clinochlore is most abundant in the region between Okenyenya and the Mitten Fold. Farther west it is present in only accessory amounts and is limited to the outer half of zone b. A distinctive feature of many crystals under crossed nicols is large purple haloes around grains of zircon. Between the Mitten Fold and Okenyenya clinochlore occurs to within 860 m of the granite.

Only one specimen containing andalusite has been found. This occurs at a distance of 1,5 km from the granite on Biesiespoort 408.

Cordierite occurs in the zone bordering on the Salem granite (zone c of fig. 9.1). From the eastern margin of the Mitten Fold, the zone stretches eastwards for a distance of 9 km and then ends abruptly against the Salem granite. West of the Mitten Fold the zone occurs all along the contact between the branite and schist. The average width of the zone is between 0,8 and 1,2 km.

Samples from the outer portions of these zones contain small anhedral crystals of cordierite full of inclusions. Nearer-the granite the cordierite usually forms large spindle-shaped poikiloblasts as much as 2 mm in diameter. Inclusions are mainly quartz, but a few biotite and muscovite flakes are also present.

In all these samples which are very fine-grained, only the assemblage biotite+cordierite+quartz±muscovite has been observed microscopically but X-ray diffraction indicates abundant plagioclase and variable amounts of potash feldspar. Small amounts of cordierite have probably been derived from clinochlore. However, there is insufficient clinochlore to account for the increase in the amount of cordierite as the size of poikiloblasts increases. The reaction biotite+muscovite+quartz→cordierite+potash feldspar appears to have taken place since biotite has not been forced aside by the growth of cordierite and within the cordierite itself biotite and muscovite inclusions are very limited in number. Samples taken within a few metres of the granite are much coarser grained and contain fairly abundant untwinned perthitic potash feldspar. In these samples zoned plagioclase is present which has a composition that varies from An_{31} in the cores of crystals eto An_{24} at the edges. Two generations of cordierite occur. Thin sections show that growth of minerals took place in the following sequence in zone c:

(1) Growth of unorientated muscovite porphyroblasts.

(2) Slight increase in the grain size of quartz and more particularly biotite, accompanied by the formation of cordierite porphyroblasts from clinochlore.

(3) Formation of cordierite by reaction between biotite and muscovite.

(4) Continued growth of groundmass quartz and biotite accompanied by the further generation of cordierite which either crystallised on the outer margins of existing porphyroblasts entrapping a few large quartz inclusions, or formed smaller anhedral crystals which lack inclusions entirely.

Sillimanite occurs in two localities. The basal Ugab quartzite north of Otjiwapeke village shows incipient alteration of muscovite to fibrolite. A sample collected on the eastern portion of Uitkoms 525 contains sillimanite in the form of fine prismatic crystals. Unaltered muscovite in association with the sillimanite occurs in both areas.

In the south-western portion of the area and due west of Otjozondjou village the schist in contact with the granite is full of *lit-par-lit* and cross-cutting granite and pegmatite dykes and veins. The zone is almost 1 km wide in the south-west but thins northwards to disappear on Uitkoms 525. West of Otjozondjou it persists for a distance of only 3 km. These dykes have two possible origins. The most obvious source for the material of the dykes is of course the Salem granite itself. However, some of the dykes are actually migmatitic partial melts. In the southwestern corner of the area melting involved the breakdown of the muscovite and biotite and the formation of almandine and potash feldspar according to the reaction:

1 muscovite + l biotite + 3 quartz ↔1 almandine + 2 potash feldspar + H_2O.

Evidence of this can be found in the presence of a little almandine (n±1,82) in a few of the granite dykes and in a few layers of schist.

West of Otjozondjou the granite and pegmatite veins farthest from the granite have intruded high-grade quartz-feldspar-biotite schists but nearer the granite *in situ* partial melting has occurred in some of the layers and migmatitic leucosome is accompanied by melanosome consisting almost entirely of biotite. This latter portion of the schist contains both injection and *in situ* granitic veins.

A partially disrupted linear body in the Salem granite 4 km east of the Ais Dome appears to be an altered pre-Salem dolerite dyke. Plagioclase, the major component, is partially saussuritised and zoned from An_{38} in the cores of crystals to An_{20} at the edges. Several large phenocrysts of plagioclase are present. Green biotite is a minor constituent and green hornblende, quartz, ore, sphene and epidote are accessory minerals. No potash feldspar was detected in thin section.

9.2.3 PT conditions of post-Damara metamorphism

9.2.3.1 *Regional metamorphism*

Orientation of micaceous minerals parallel to the S_2 cleavage in the regionally metamorphosed schist indicates crystal growth during the late stages of the F_2 phase of folding. Miller (1974) has, however, shown that the highest temperatures were reached after tectonism had altogether ceased.

In the plagioclase-bearing rocks of the Ais Dome there is no evidence of the reaction muscovite+quartz↔potash fe ldspar+sillimanite+H_2O. Under conditions of $P_{H2O}=P_{total}=3$ and 5 kb the analysed Lower Naauwpoort samples (Ab/An effectively infinite, table 4.2a) will start to melt at temperatures of between about 660° and 650°C (Winkler 1976, p. 290). Because of the very high proportion of Qtz+Or+Ab (95 per cent) in these rocks (table 4.2a) a large amount of melt will form only a few degrees above the solidus under saturated conditions (Tuttle and Bowen 1958).

In the Naauwpoort rocks, however, non-saturated conditions appear to have prevailed as only a relatively small amount of mica is present. In figure 9.6 the probable PT field of the Ais Dome is shown together with the curves for the beginning of anatexis and the reaction muscovite + quartz ↔ potash feldspar+sillimanite+H_2O. Since the Ab/An ratio is effectively infinite for some of the rocks, the earliest melts will form at the ternary minimum in the system Or-Ab-Qtz-HP (curve a) and will be water-saturated (P probably >3,5 kb). However, as the volume of melt increases, saturation will decrease and in order to produce more melt the temperature must be raised (Tuttle and Bowen 1958, p. 122; Brown 1970; Winkler 1976, p. 307). The Naauwpoort rocks contain very little water so that the amount of saturated melting that could have taken place would have been very limited. The pegmatites probably represent saturated melts that formed at pressures greater than 3,5 kb and' temperatures in the region of 650° to 670 °C. Complete remobilisation took place at higher temperatures and mainly at greater depths under unsaturated conditions.

A more precise indication of pressure can be obtained by a consideration of the calc-silicate assemblages. Experimental work has shown that each of the minerals talc, tremolite, diopside and forsterite can form over a wide temperature range and the actual temperature of formation is determined by the partial pressures of CO_2 and Hp (Metz and Trommsdorff 1968; Metz and Puhan 1971; Winkler 1976). At high partial pressures of CO_2 (P_{CO2}) it is even possible for diopside to form directly from dolomite and quartz without either talc or tremolite forming first. The experimental curves of Metz and Trommsdorff (1968), reproduced in figures 9.3 and 9.4, show that in the absence of a knowledge of P_{CO2} at the time of reaction it is not possible to give an accurate indication of the temperature at which most assemblages developed.

However, reactions 4, 5, 8 and 14 (figs 9.3 and 9.4) do appear to occur over very limited temperature and P_{CO2} ranges and could therefore be useful indicators of pressure if temperature were known and vice versa. At Okombahe the reaction 1 Dol + 2 Qtz ↔ Diop + $2CO_2$(reaction 8, fig. 9.3) appears to have taken place between dolomite in marble and quartz of granite veinlets which intruded the marble during metamorphism. No forsterite is present so that reaction 14, occurring at a temperature of 45° to 75°C higher than reaction 8, has not taken place. The work of Metz (1970) and Metz and Puhan (1971) and the data given by Winkler (1976, pp. 114 and 121) show that the shapes of the curves for reactions 1 and 6 scarcely change for P_{CO2}<0,7 as total pressure is increased. An increase in pressure from 1 to 5 kb is accompanied by a rise in the temperature of the reactions between 135° and 160°C. Assuming that the relationships between the curves for reactions 4, 5, 8 and 14 and the curves for reactions 2, 6, 9 and 11 at high P_{CO2} remain more or less the same as total pressure increases, then reaction 8 may be expected to occur at a minimum temperature of between 615° and 645°C at a total pressure of 5 kb (Winkler 1976 gives a temperature of 625°C).

Winkler (1976) shows reaction 14 occurring at a temperature of 700°C at a 5 kb pressure. At this pressure water-saturated melting of granitic rocks begins at 650°C (Winkler 1976, p. 290) so that any granitic intrusion into the carbonate at Okombahe village could have taken place over a maximum temperature range of 50°C only without forsterite forming. The observed reaction, involving a granitic melt, will not occur at a pressure of less than 4 kb, for at this value the temperature at which reaction 14 will take place will be about 660°C and melting only starts at 655°C at this pressure.

If the assumption made above regarding the constant relationship between the reaction curves with changing pressure prove to be correct then the mineral associations indicate that a pressure of 4 to 5 kb pertained in the south-eastern corner of the area.

The rocks of the Ais Dome show that, apart from P_{CO2} and P_{H2O}, PT conditions were more or less constant throughout, i.e. there is no thermal envelope. These rocks therefore only show the effects of regional metamorphism and since the structure is surrounded by granite (see also Haughton *et al.* 1939) it is probable that conditions were very similar to those in the vicinity of the Okombahe village.

9.2.3.2 *Thermal metamorphism*

Intrusive late differentiates of the Salem Suite have produced a thermal overprint on the regional metamorphic assemblages of the Naauwpoort Formation and the Kuiseb schist. The limit of thermal metamorphism is marked by a spotting of the schist by clusters of biotite flakes about 12 km from the granite. Samples from the basal Ugab quartzite at the granite contact north of Otjiwapeke village show the incipient breakdown of muscovite to fibrolite. This reaction has enabled the minimum PT conditions of post-Damara thermal metamorphism in the vicinity of the southern margin of the Mitten Fold to be fairly accurately established. In figure 9.7 curves for the breakdown of muscovite in the presence of quartz (Althaus *et al.* 1970) and for the beginning of melting (Winkler 1976) are shown in addition to two presentations of the aluminium-silicate phase diagram (Althaus 1969; Holdaway 1971). The incipient breakdown of muscovite to sillimanite is limited to temperatures and pressures greater than those for point Y on curve *a*. However, samples of metamorphosed plagioclase-bearing Naauwpoort volcanics taken at the contact with the granite contain only muscovite and no sillimanite. These therefore indicate that the temperatures of curve a were only just reached and that slight variations in the composition of muscovite and plagioclase were probably important in determining whether Or not it was stable under the prevailing conditions. At pressures and temperatures lower than those of point Y, andalusite and not sillimanite is stable. At pressures and temperatures greater than the point at which curves *a* and *b* intersect, melting can occur. Incipient melting of the Naauwpoort rocks (Ab/An effectively infinite) underlying the sillimanite-bearing Ugab quartzite is indicated by the presence of numerous secretion pegmatites. A minimum pressure of about 3,5 kb is therefore indicated in the region of the southern margin of the Mitten Fold (fig. 9.7).

North-east of Otjiwapeke village the minimum temperature of the schist, 1 km away from the granite, can also be established. At 3,5 kb the reaction clinochlore+quartz↔ cordierite (corresponding to the transition from zone b to zone c) takes place at a temperature of 605°C (Fawcett and Yoder 1966). On Biesiespoort 408 diopside first appears in the dolomite 1 km from the granite. At 3,5 kb diopside forms from tremolite, calcite and quartz at a temperature of 615°C (Metz 1970, p. 235). This corresponds very well to the temperture for the breakdown of clinochlore. The first appearance of diopside marks the beginning of the hornblende-hornfels facies of metamorphism (Winkler 1976, p. 30).

It is not possible to indicate where boundaries between thermal and regional metamorphic zones should be drawn as these merge into one another.

In conclusion it can be stated that the mineral assemblages indicate conditions of high temperature and intermediate pressure along the southern margin of the area. Under these conditions remelting of the Naauwpoort metavolcanics led to the formation of the Sorris-Sorris Granite. Intrusion of the Salem granite produced a contact aureole with a typical Abukuma-type mineral facies series.

10. EVOLUTION OF THE NOSIB, SWAKOP AND MULDEN BASINS IN PRESENT AREA

Areas immediately to the north-east and north-west will also be considered in this discussion where possible. These are shown in relation to the present area in figure 8. 1. A summary of the sequence of events is given below:

(1) Uplift and erosion in the north coincided with deposition of conglomerate on the southern flanks of the Kamanjab Inlier. Sandstone and graywacke were deposited farther south.

(2) Large-scale east-west block faulting, accompanied by localised acid volcanism, produced graben-like depressions to the south. A thick sequence of ash flows accumulated in the newly formed tectonic depressions.

(3) Local very slight uplift and erosion occurred which were followed by general but uneven subsidence and marine encroachment over most of the area. Shallow-water conditions prevailed and mainly carbonates were deposited. Volcanism overlapped with this phase of deposition.

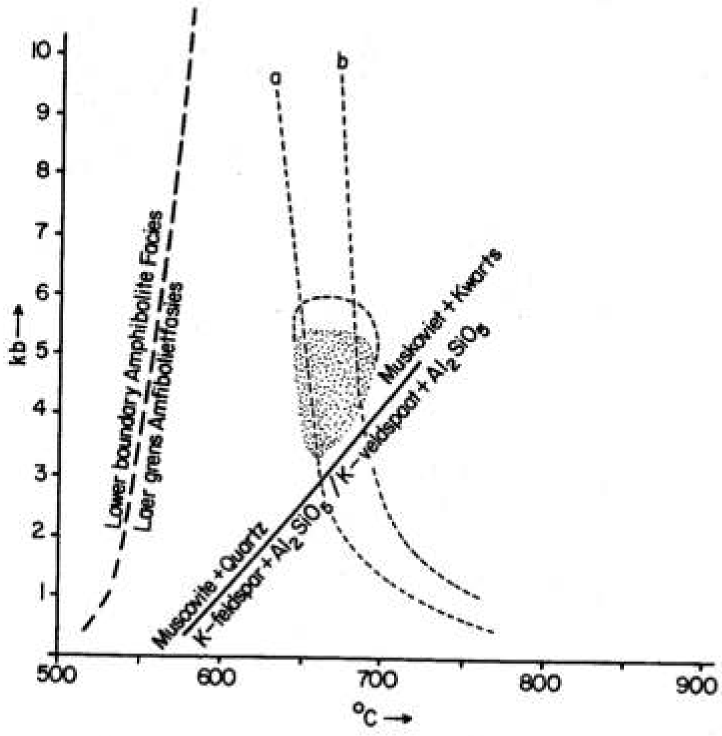


Fig. 9.6 – Possible PT field of post-Damara metamorphism within the Naauwpoort rocks of the Ais Dome. Curve a – beginning of melting – water-saturated minimum for granitic rocks with plagioclase of composition An_0. Curve b – beginning of melting of many paragneisses under water-saturated conditions; plagioclase in the oligoclase–andesine range. Curves after Winkler (1976).
Moontlike DT-veld van na-Damarametamorfose in die Naauwpoortgesteentes van die Aiskoepel. Kurwe a – begin van smelting – waterversadigde minimum vir granitiese gesteentes met plagioklaas met samestelling An_0. Kurwe b – begin van smelting van baie paragneise onder waterversadigde toestande; plagioklaas in die oligoklaas–andesiengebied. Kurwes volgens Winkler (1976).

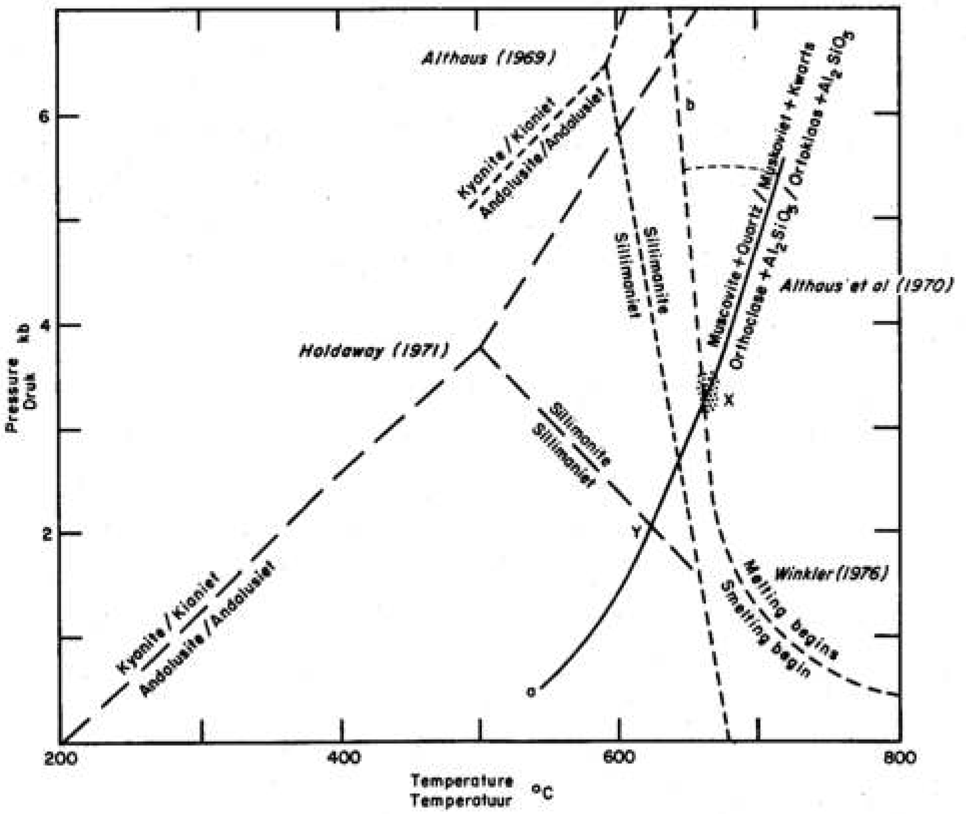


Fig. 9.7 — Probable PT conditions of thermal metamorphism at the contact of the Salem granite in the vicinity of the Mitten Fold (stippled area) shown in relationship to experimentally determined phase equilibria; aluminium-silicate phase boundaries — Althaus (1969) and Holdaway (1971); muscovite + quartz — Althaus *et al.* (1970); beginning of melting, (Ab/An=∞ — Winkler (1976).
Waarskynlike DT-toestande van termale metamorfose op die kontak van die Salemgraniet naby die Mittenplooi (gestippelde gebied) getoon in verbouding tot die eksperimenteel bepaalde fase-ewewigte; aluminiumsilikaat-fasegrense — Altbaus (1969) en Holdaway (1971); muskoviet + kwarts — Altbaus et al. (1970); begin van smelting (Ab/An=∞ — Winkler (1976).

(4) A second period of local uplift and erosion was accompanied by widespread glaciation during which at least four glacial retreats occurred. Volcanism ceased during this glaciation.

(5) A long period of deposition followed during which a little carbonate and a great deal of pelitic sediment accumulated.

(6) Deformation of the sediments began either towards the end of this depositional period or soon after its completion. This caused local uplift and erosion of the sedimentary pile and of the basement areas farther north. Towards the end of this phase, the Mulden sediments were deposited in the intermontane areas. These were folded during the F_2 phase of deformation.

(7) Intrusion of the differentiated Salem granite and the Sorris-Sorris Granite occurred subsequent to the F_2 deformation.

Deposition was initiated during Nosib times, when boulder-conglomerates accumulated on the southern flanks of the Kamanjab Inlier (Kranspoort Member: Clifford, Nicolaysen and Burger 1962) and the Welwitschia Ridge (Naauwpoort Formation: Frets 1969) following tectonic uplift to the north. To the south of the Welwitschia Ridge quieter depositional conditions caused the deposition of feldspathic sandstones and graywackes (now metamorphosed).

After these sediments accumulated, east-west faulting occurred (Bethanis Fault in the Huab-Khorixas area and Summas Fault in the present area) resulting in the formation of huge graben-like depressions on the southern flank of the Kamanjab Inlier (the author considers the Welwitschia Ridge and the gneiss on the northern edge of the Summas Mountains to be merely humps on the flank of the Kamanjab Inlier). Localised volcanism, directly associated with faulting, produced large quantities of acid pyroclastic rocks which accumulated almost entirely in the newly formed tectonic depressions. In the west these overlie the Naauwpoort sediments conformably (Frets 1969, p. 51), whereas outcrops in the present area show that extrusions were able to flow for a distance of more than 60 km in a southerly direction.

Granoblastic quartz-microcline rocks in the Nosib Group near Henties Bay (referred to as the Tsaun Formation by Botha *et al.* 1972 and Botha 1978) are identical to recrystallised Naauwpoort rocks in thin section (Schoeman 1970, plate II; Van Reenen 1970, plate VIII). They are almost in line with the Naauwpoort Ridge and could well be the southward extension of the Naauwpoort Formation. If so, they indicate that the extrusions flowed a distance of at least 180 km.

At the end of the main phase of volcanism, during which more than 6 600 m of volcanics accumulated, very slight uplift and erosion occurred in a few places. This was immediately followed by a general but uneven subsidence and rapid marine encroachment over almost the whole area. The only region scarcely affected was the central portion of the Kamanjab Inlier. The thickness changes of the earliest sediments, mostly carbonates, reflect the uneven rate of subsidence. Very slow deposition producing laminated dolomite and only a thin sequence occurred where subsidence was minimal, i.e. in the central region of the Naauwpoort Ridge. Here algal colonies thrived in the shallow water, producing thick reef deposits. Conditions appear to have been exceptionally calm in this region for pelitic sediment was able to accumulate (Orusewa, Moedhou and Groenpoort sections, fig. 5.2).

On the flanks of the Kamanjab Inlier reasonably thick carbonate deposits accumulated. However, the amount of subsidence increased in a southerly direction away from the Kamanjab Inlier and in an easterly direction away from the Naauwpoort Ridge. Thus the thickest deposits, which contain more schist than carbonate, occur in the Okonguarri Anticline.

At this time rather unusual depositional conditions existed on the north-eastern edge of the Summas Mountains. There were still intermittent movements on the Summas Fault and on smaller subsidiary faults in the gneiss. Rapid erosion of scarps formed by faulting produced unsorted conglomeratic clastic wedge deposits that are interbedded with carbonate rocks. Concomitant extrusions of pyroclastic rocks and lavas, associated with the closing stages of Naauwpoort volcanism, either partially or completely overwhelmed carbonate deposition at times.

Following on this phase of deposition, local uplift and erosion took place in the region of the Summas Mountains, Welwitschia Ridge and Kamanjab Inlier and were accompanied by very widespread glaciation. Earlier deposits of carbonate covering the Summas Mountains and the Welwitschia Ridge were removed completely as shown by the abundant dolomite inclusions in the nearby Chuos Formation deposits. The maximum amount of deposition took place fairly near the centres of erosion i.e. on the outer flanks of the Kamanjab Inlier (Landeck Member of Clifford, Nicolaysen and Burger 1962), and on the eastern side of the Summas Mountains, but it is only in the latter locality that true tillite occurs. All other deposits are glaciomarine or fluvioglacial and conformable with underlying layers, thus proving that uplift was only local. The earliest recognisable glacial sediments are of equivalent age to schist elsewhere and it was only during the later stages that the Chuos Formation was deposited over the whole area. As is the case with the Okotjize Formation, the Chuos Formation is also very thin on top of the Naauwpoort Ridge.

At least four glacial retreats occurred during which thin non-glacial deposits accumulated. These lack inclusions. Deposition of micritic carbonate during the last two retreats appears to have been fairly widespread. Deposits of siliceous iron formation are associated with the whole of the glacial episode.

The Chuos glaciation also coincided with the cessation of volcanism in the Summas Mountains and the termination of volcanism and subvolcanic igneous activity in the Huab-Khorixas area. In both areas the Chuos Formation contains pyroclastic deposits and in the latter area it is cut by felsitic dykes.

Following the final glacial retreat, a small amount of pelitic sediment was able to accumulate before conditions favouring carbonate deposition set in once again over almost the whole area. Only in places in the west do pelitic sediments form a continuous succession. The increase in thickness of the carbonate unit in an easterly direction away from the Naauwpoort Ridge indicates that the rate of subsidence was almost the same as before. Although these sediments are very thin over the Naauwpoort Ridge, they reach a fairly average thickness of about 150 km in the rest of the basin. Along the Kamanjab Inlier, however, this thickness increases to about 1

000 m. Strong evidence for sedimentation in shallow water over almost the whole basin is provided by stromatolitic structures in the deposits along the edge of the Kamanjab Inlier (Frets 1969), by the fetid odour and graphitic impurities (probably both organic in origin) of the limestone of the Karibib Formation south-west of Otjozondjou village and near the southern limit of Okonguarri Anticline, and by layers of oolitic chert north of the Summas Mountains and on the southern edge of the Kamanjab Inlier (Frets 1969).

There now followed a long period of subsidence and deposition in which mainly graywackes and pelitic sediments accumulated. At times conditions conducive to the deposition of psammites and carbonates prevailed locally. Subsidence, which scarcely affected the southern edge of the Kamanjab Inlier, took place along two hinge lines, one coinciding with the edge of the Welwitschia Ridge and its extension to the Summas Mountains and the other joining the Summas Mountains along a slightly arcuate line with the small pre-Nosib inlier a few kilometres south-east of Outjo. These hinge lines coincide almost exactly with structures which formed the edge of the main Nosib basin in this area, the huge graben-like Bethanis and Summas Faults. It must be emphasised, however, that there is no evidence for post-Chuos rejuvenation of the Summas Fault.

South of these hinge lines a great deal of subsidence took place allowing for the eventual deposition of almost 10 000 m of detrital sediment. It is probable that the rate of subsidence was slower in the region of the Naauwpoort Ridge in keeping with the earlier subsidence pattern, but there is no evidence to prove this. To the north the pelites thinned out against the sediments already deposited on the flanks of the Kamanjab Inlier and only a relatively small amount of pelitic material was deposited north of the hinge lines. Preserved remnants of the latter occur in the south-western corner of Toekoms 508 in the Khorixas area and form part of the Okaua member (Clifford 1967) east of the Summas Mountains. It is impossible to say how much schist was deposited on the flanks of the Kamanjab Inlier but the features described below indicate that the amount was probably very limited.

In the Huab-Khorixas area Frets (1969, p. 103) has observed pre-Mulden gorges eroded in Swakop carbonate to a depth of 150 m. Similar gorges in the pre-Damara gneisses are as much as 75 m deep. In the vicinity of the Summas Mountains the Ugab Subgroup succession overlying the Naauwpoort Formation was removed during the Chuos glaciation. From the topographic detail shown in figure 7. 1 it can be seen that pre-Mulden erosion made a deep incision into the pre-Damara rocks after removing all the sediments of the Swakop Group. This deep penetration of pre-Mulden erosion was probably assisted by two factors-the thinning of the Swakop succession as a result of slumping which followed uplift, and a zone of least resistance to erosion in the form of the Summas Fault, over which the Mulden sediments now lie. The present outcrops of the Karibib Formation give indications of what its thickness might have been. The level reached by pre-Mulden erosion, despite being facilitated by the points mentioned above, seems to preclude any great thickness of Swakop sediment in the Summas Mountains region and the Kuiseb schist, if present there at all, was probably very thin. There is also evidence that no pelitic equivalents of the Kuiseb schist were deposited north of the Kamanjab Inlier. North-west of Kamanjab, Mulden sediments rest unconformably on gently folded Otavi Group carbonates. Farther north, beneath the thick cover of Kalahari deposits, the Otavi Group is scarcely deformed. It lacks pelitic sediments entirely and is conformably overlain by the Mulden Group. *

Deformation probably started towards the end of the Khomas sedimentation or followed fairly soon after its completion. In the present area Swakop sediments and Naauwpoort volcanics were first folded along east-west axes into huge anticlinal and synclinal structures with wavelengths of several kilometres. Slumping of partially consolidated 'carbonates occurred to the north of the Summas Mountains. Uplift during this phase of folding resulted in erosion, locally intense, and deposition of Mulden sediments in intermontane areas. The second phase of deformation was much more intense than the first and culminated in shear folding and the development of a regional cleavage. It produced structures with axes orientated in a north-north-easterly direction in the east and a north-westerly direction in the west. The Mulden Group was folded during the second phase of deformation.

As deformation progressed the intensity of metamorphism increased but reached a climax after the final shear folding (Miller 1974). Anatexis in the south under conditions of high temperature and intermediate pressure produced the Sorris-Sorris Granite from the Naauwpoort volcanics. Post-tectonic intrusion of the Salem granite into lower pressure regions farther north produced a thermal aureole with typical Abukuma-type mineral assemblages. The intrusion of the Sorris-Sorris Granite into the Salem granite was the last major event of this grand cycle in the present area.

11. POST-DAMARA GRANITES

11 . 1 SALEM SUITE

The distribution, petrography, geochemistry and petrogenesis of the rocks of the Salem Suite have been discussed in detail by. Miller (1974), and only a summary of the main features of the Suite is given here.

The rocks of the Suite occur south of a line which roughly joins the north-western corner of the area investigated with the south-eastern corner. Very even-weathering of the granite has produced a flat topography which is broken only by more resistant outcrops of younger rocks or by the incision of the Ugab River. Most of the granite, which is typically very coarse grained and porphyritic, is covered by a thin veneer of coarse granitic debris and exposures are generally limited to the main water-courses.

The members of the Suite form a differentiation-sequence marginal zone, 1 km wide, of hornblende-biotite-quartz diorite at Otjozondjou. This zone grades through quartz monzodiorite into the main body of the Salem granite which has the mineralogical composition of quartz monzonite near the diorite but becomes progressively more potassic towards the south and west where it is a true granite.

* Personal communication, R. M. Hedberg, Harvard University.

Recent determinations of the PT conditions of regional metamorphism (Sawyer 1978) and numerous detailed observations of the contact between - the Salem granite and Kuiseb schist .by the author in several localities, has placed serious doubts on the autochthonous origin of the Suite as proposed by Miller (1974).

A few thin pegmatites intrude the granite on Sorris-Sorris 186.

11.2 SORRIS-SORRIS GRANITE

The name "Sorris-Sorris granite" was proposed by Martin (1965, p. 44) for pink medium-grained granite occurring along the Ugab River on the farm Sorris-Sorris 186. Unfortunately, because the Salem granite is morphologically less prominent than the Sorris-Sorris Granite and usually lies hidden beneath a thin cover of granitic debris, subsequent authors have included all the granite north of the Ugab River under the name Sorris-Sorris Granite.

Outcrops of the Sorris-Sorris Granite are typically quite prominent. The granite occurs mainly in the form of dykes but several stocks of variable size and quite irregular shape occur, the largest of these being 11 km long and 3 km wide. Most of the larger bodies occur along the U gab River and in the northwestern portion of the area. The large outcrop area on the north-western flank of the Ais Dome is actually underlain by Salem granite but this contains so many dykes of Sorris-Sorris Granite that the latter predominates (fig. 11. 1). Several thick dykes with a north-easterly orientation occur between the Ais Dome and the Mitten Fold. Narrow dykes are extremely abundant in the area between Sorris-Sorris 186 in the west and Otjongundu village in the east (fig. 11.2) and the easternmost limit of the Sorris-Sorris Granite is about 2 km east of Otjongundu village. Virtually all the Sorris-Sorris Granite is intrusive into the Salem granite. A few small stocks and dykes cut the Naauwpoort metavolcanics of the Ais Dome and the southern margin of the Mitten Fold, and only one relatively small dyke-like body is intrusive into the Kuiseb schist.

Although the Sorris-Sorris Granite was generated during the post-Damara metamorphism, it was emplaced after the post-tectonic Salem granite which it freely intrudes.

11.2.1 Petrography

The Sorris-Sorris Granite is medium grained in most outcrops. A few narrow dykes of a later porphyritic phase cut the Sorris-Sorris Granite on the southern portion of Irene 413 and most of the larger bodies are cut by a few very thin homogeneous pegmatite dykes. Three varieties of the Sorris-Sorris Granite have been distinguished on the basis of colour. Red- and pink-coloured varieties, which can readily be distinguished from each other, predominate and both form stocks and dykes. Neither is limited to any particular region. The map shows a greater concentration of the red variety in the west, but in the east approximately equal numbers of red and pink dykes occur. A grey-coloured variety cuts the skarn on the northern margin of the Ais Dome and is also found intrusive into the underlying metamorphosed Naauwpoort volcanics.

The modes of eight Sorris-Sorris Granite samples are given in table 11.1. Mineralogically all have the composition of granite. There is no regular variation in the proportions of the major components present.

On average the red variety contains more muscovite than the pink variety and the average muscovite/ biotite ratio is higher in the pink than in the red variety. Allanite occurs only in the pink variety.

Textures are granitic to allotriomorphic granular. Microcline is finely perthitic and fresh. Plagioclase is both fresh and strongly altered. Clear albite rims are numerous at plagioclase/microcline contacts (Miller 1973). Unaltered crystals have an average composition of An_{22}. Only in some of the specimens is the plagioclase zoned, but preferential alteration of the cores of crystals has produced a false reverse zoning with compositions ranging from An_0 to An_7 in the cores of crystals and from An_{13} to An_{17} in the outer zones. All strongly altered grains have compositions of An_0.

Most samples of the grey variety of Sorris-Sorris Granite contain much more microcline than plagioclase. Biotite and muscovite are either absent or present in only accessory amounts. One small body intrusive into the skarn on the northern margin of the Ais Dome contains small amounts of tremolite and calcite indicating contamination. Plagioclase in all samples is similar in composition to that in the red and pink varieties of the granite.

Table 11.1 MODES OF RED AND PINK VARIETIES OF SORRIS-SORRIS GRANITE

	Red variety				Pink variety			
Sample No.	RM 654	RM 663	RM 667	RM 673	RM 662	RM 664	RM 665	RM 666
Quartz	31,1	31,9	27,6	30,3	26,3	29,7	32,2	36,7
Microcline	32,2	36,6	38,1	28,8	38,0	33,0	29,3	40,1
Albite rims	0,8	2,3	1,6	1,7	3,4	3,2	2,3	2,3
Plagioclase	32,5	25,8	24,6	31,5	27,8	29,8	29,7	17,4
Biotite	1,7	0,7	2,7	1,1	2,8	3,1	2,6	0,5
Muscovite	1,2	2,3	4,2	5,0	0,4	0,3	3,2	1,7
Ore	0,5	0,4	1,2	1,0	1,2	0,7	0,7	1,1
Accessory minerals	Cc	Zr Ap	Zr Cc Ap	Zr Cc	Zr Al	Zr Al Ap	Zr Al Ap	Zr Al Ap

Cc=calcite.
Zr=zircon.
Ap=apatite.
Al=allanite.

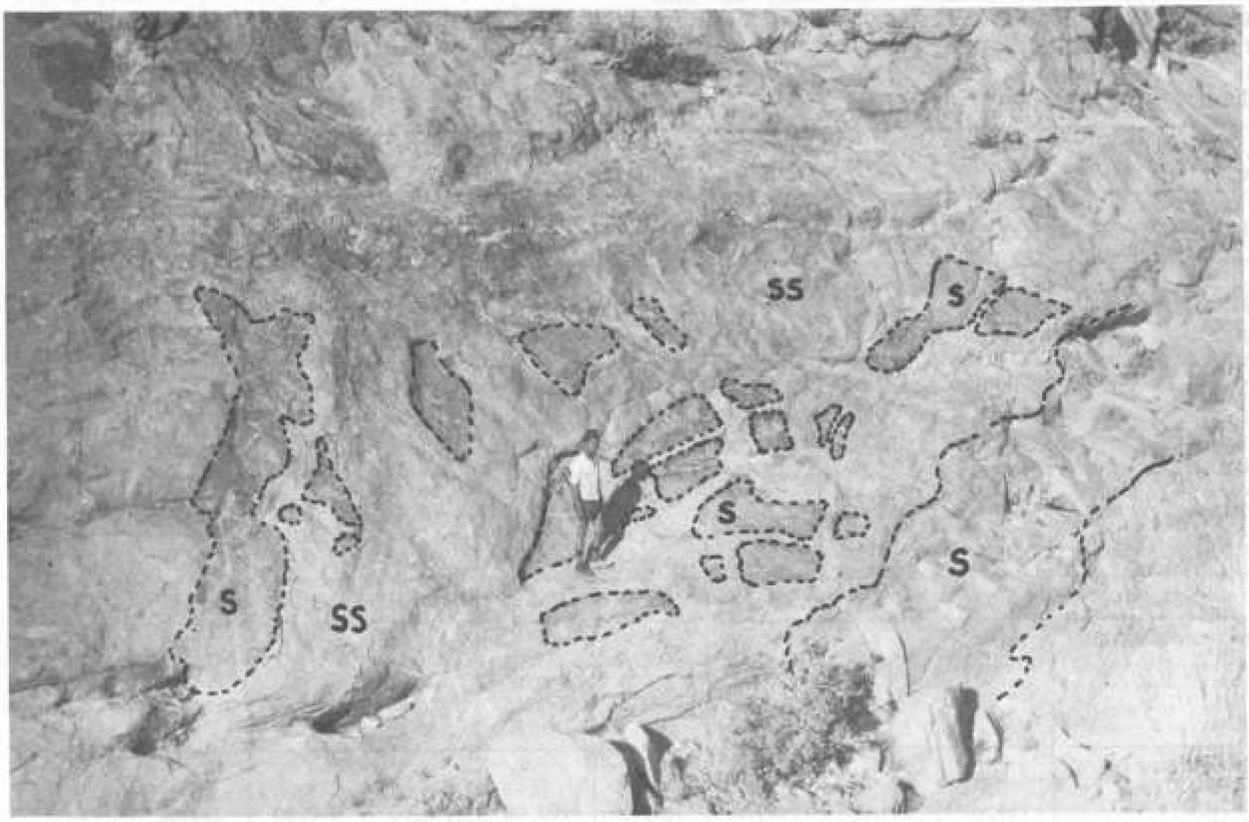


Fig. 11.1—Salem granite (S) intimately intruded by Sorris-Sorris Granite (SS) 3 km north-west of Ais Dome.
Salemgraniet (S) diep binnegedring deur Sorris-Sorris-Graniet (SS) 3 km noordwes van Ais-koepel.

Fig. 11.2—Salem granite cut by numerous narrow dykes of Sorris-Sorris Granite.
Salemgraniet gesny deur talle smal gange van Sorris-Sorris-graniet.

11.2.2 Geochemistry

Four samples of each of the red and pink varieties of the Sorris-Sorris Granite were analysed. This number was considered necessary in order to ensure a confirmation of the common origin of both varieties and the origin of the Sorris-Sorris Granite as a whole. The grey variety was not analysed because of contamination by the nearby skarn. The analyses are presented in table 11.2 and cation proportions and mesonorms in table 11.2 (a).

Table 11.2 CHEMICAL COMPOSITION OF ANALYSED SORRIS-SORRIS GRANITE SAMPLES

	Red variety				Pink variety				
Sample no.	RM 654	RM 663	RM 667	RM 673	RM 662	RM 664	RM 665	RM 666	(a)*
SiO_2	72,47	74,67	70,49	71,70	72,49	73,29	71,16	72,97	73,86
TiO_2	0,22	0,10	0,38	0,25	0,29	0,18	0,24	0,24	0,20
Al_2O_3	13,91	13,23	13,84	13,69	13,96	13,44	13,80	13,25	13,75
Fe_2O_3	0,60	0,30	0,98	0,68	0,69	0,55	0,45	0,63	0,78
FeO	1,29	0,57	1,41	1,27	1,44	0,93	1,15	1,15	1,13
MnO	0,04	0,03	0,05	0,05	0,04	0,02	0,02	0,04	0,05
MgO	0,43	0,10	1,91	0,45	0,47	0,25	0,30	0,20	0,26
CaO	1,28	0,56	1,27	1,20	1,27	1,14	1,47	1,24	0,72
Na_2O	3,63	3,69	2,96	3,46	3,24	3,53	3,62	3,04	3,51
K_2O	5,00	5,33	6,15	5,22	5,56	5,30	6,10	5,67	5,13
P_2O_5	0,07	0,05	0,11	0,06	0,10	0,04	0,05	0,12	0,14
l.o.i.	0,56	0,66	0,96	1,36	0,56	1,21	0,95	0,61	0,47†
H_2O	0,18	0,13	0,08	0,17	0,14	0,63	0,17	0,08	—
Totals	99,68	99,42	100,59	99,56	100,25	100,51	99,48	99,24	—
Trace elements, ppm:									
Rb	253	288	297	266	228	318	294	250	—
Ba	921	322	585	741	1 386	511	764	372	—
Sr	170	49	89	115	215	96	141	112	—
Cu	24	19	1	1	22	19	19	20	—
Inter-element ratios:									
(Na+K)/Al	0,93	1,02	0,99	0,95	0,95	0,98	1,06	0,99	0,94
K/Rb	164,00	154,00	192,00	163,00	202,00	138,00	172,00	188,00	—
K/Ba	45,00	138,00	87,00	58,00	33,00	86,00	61,00	126,00	—
Ba/Rb	3,60	1,10	2,00	2,80	6,10	1,60	2,60	1,50	—
Ba/Sr	5,40	6,10	6,60	6,40	6,50	5,30	5,40	3,30	—

*=Average alkali granite, Nockolds (1954).
†=H_2O^+.
Analyst: Geochemistry Department, University of Cape Town.

Table 11.2 (a) CATION PROPORTIONS AND MESONORMS OF SORRIS-SORRIS GRANITE SAMPLES

	Red variety				Pink variety			
Sample no.	RM 654	RM 663	RM 667	RM 673	RM 662	RM 664	RM 665	RM 666
Cation per cent:								
Si	68,31	70,57	65,92	68,28	68,10	69,33	67,27	69,43
Ti	0,16	0,08	0,27	0,18	0,21	0,13	0,18	0,18
Al	15,46	14,75	15,26	15,37	15,47	14,99	15,38	14,87
Fe^{3+}	0,43	0,22	0,69	0,49	0,49	0,40	0,33	0,46
Fe^{2+}	1,02	0,46	1,11	1,02	1,14	0,74	0,91	0,92
Mn	0,04	0,03	0,04	0,05	0,04	0,02	0,02	0,04
Mg	0,61	0,15	2,67	0,64	0,66	0,36	0,43	0,29
Ca	1,30	0,57	1,28	1,23	1,28	1,16	1,49	1,27
Na	6,64	6,77	5,37	6,39	5,91	6,48	6,64	5,61
K	6,02	6,43	7,35	6,35	6,67	6,40	7,36	6,89
P	0,06	0,05	0,09	0,05	0,08	0,04	0,05	0,10
Mesonorm:								
Quartz	28,13	30,07	25,82	27,89	28,32	28,64	21,78	29,92
Orthoclase	26,94	30,59	29,08	28,58	29,67	30,29	36,79	32,23
Albite	33,18	33,82	26,84	31,95	29,52	32,38	33,18	28,05
Anorthite	5,22	2,15	4,30	4,83	4,71	4,87	3,48	4,66
Muscovite	1,46	1,40	1,68	1,44	2,04	0,36	—	1,02
Biotite	3,85	1,36	9,23	3,86	4,21	2,43	—	2,69
Actinolite	—	—	—	—	—	—	3,16	—
Diopside	—	—	—	—	—	—	0,55	—
Sphene	0,47	0,22	0,81	0,54	0,62	0,39	0,52	0,52
Magnetite	0,64	0,32	1,04	0,74	0,74	0,59	0,49	0,68
Apatite	0,15	0,11	0,24	0,13	0,22	0,09	0,11	0,26
Ratio:								
Ab/An	6,40	17,80	6,20	6,60	6,30	6,60	9,50	6,00

All the samples are alkaline and compare very well with Nockolds's (1954) average alkali granite, though some contain a little more MgO (e.g. RM 667) and all but one of the samples (RM 663) contain a slightly higher proportion of CaO. Proportions of Na_2O and K_2O are comparable with Na_2O and K_2O in Nockolds's average but the latter oxide tends to be slightly higher in most of the Sorris-Sorris samples.

Comparisons with the analysed Naauwpoort rhyolites (table 4.2) reveal certain differences, some small but others quite significant. The granite samples are slightly less siliceous. They contain a little more Al_2O_3 and MgO and considerably more CaO. The average Fe^{2+}/Fe^{3+} ratio exceeds 1 in the granite and is less than 1 in the rhyolite, as is to be expected. The granite contains more potash than soda but is not as highly potassic as are some of the rhyolites. It is also slightly less alkaline than the rhyolite. Mesonorms are very similar to the mesonorm of the most sodic sample of rhyolite (RM 475).

A consideration of the relative trace-element abundances shows that on average the granite has a little more Rb, much more Sr, and less Ba than the Naauwpoort rhyolite. However, the K/Rb and K/Ba ratios show that relative to K there is more than twice as much Rb in the granite but that there is about the same amount of Ba. The Ba/Rb ratio, although somewhat variable, is on the whole low, suggesting that some differentiation of the magma may have taken place.

Copper in the Sorris-Sorris Granite can be associated with Fe and Na. Cu^{2+} is similar in size to Fe^{2+} and Na^{+}. Small quantities of copper in the igneous environment substitute for Na^{+} and Ca^{2+} in plagioclase and apatite and also enter minerals containing Fe^{2+}. However, due to the more covalent nature of the Cu-O bond, the concentration of Cu will increase during fractionation. When a separate Cu-bearing sulphide phase appears, the Cu content of the previous host minerals will drop sharply (Taylor 1965, p. 176). In the Sorris-Sorris Granite the Cu can be expected in plagioclase, biotite and ore, but no relationship exists between Cu and Fe, Ca or Na in the samples. The concentration of Cu in most of the samples is about double that for granite as quoted by Taylor (1965).

The increase in Sr content can probably be attributed to association with Ca, but there is no correlation between the relative abundances of these two elements.

The additional soda may have accompanied the Ca or, alternatively, it may actually have been present in the volcanic pile in the form of interfingering of Na-rich flows from the Huab-Khorixas area (Frets 1969). Mobilisation would have produced an average composition.

The relatively low K/Rb ratios and the low Ba/Rb ratios in comparison to those of the analysed volcanic rocks point to a certain degree of differentiation and it is possible that some crystal settling may have taken place in the Sorris-Sorris granite magma in the same way as crystal settling in the Salem granite magma occurred (Miller 1974). Intrusion of the granite took place into a hot environment because there are no signs of chilling along contacts with the Salem granite.

There is no apparent difference in the red and pink varieties of the Sorris-Sorris Granite. Ultrametamorphism of the Naauwpoort rhyolites, which eventually led to remobilisation and production of the Sorris-Sorris Granite has already been discussed. However, the slight chemical differences that do exist between the Sorris-Sorris Granite and the Naauwpoort rhyolite indicate that the process did not merely involve fusion and recrystallisation. The higher CaO content of the granite points to some contamination of the magma, probably by liquid formed from the underlying rocks. As the base of the lower Naauwpoort Formation is not exposed, it is not possible to say what the underlying rocks were, but they could either have been basement gneiss or Nosib Group sediments. The latter are widespread in the Damara belt and it is quite possible that they underlie the Naauwpoort volcanics.

The reasons why the Sorris-Sorris Granite is considered to be a remobilisation product of the Naauwpoort rhyolites are set out below:

(1) Both rock types are alkaline and have similar chemical compositions.

(2) Field evidence for both partial and complete fusion has been found.

(3) Ab/An ratios of the rhyolites are very high. Those of the granite are comparable and indicate an approximate difference of only 10°C in the water-saturated minimum melt temperatures of both rocks (Winkler 1976, p. 293).

(4) Strongly recrystallised equivalents of the rhyolites can still be found in regions that underwent high-grade metamorphism. The Naauwpoort Formation is more than 6000 m thick in the Mitten Fold and, because of the very fluid nature of ash flows, is unlikely to have been much thinner in regions only a little farther south.

(5) The granite is limited to the regions that have undergone high-grade metamorphism.

(6) Most of the granite occurs in the vicinity of the Ais Dome-Mitten Fold, i.e. where metamorphosed Naauwpoort volcanics are exposed.

12. KAROO SEQUENCE

The Karoo Sequence in the present area comprises sedimentary rocks of the Dwyka and Omingonde Formations, together with later sills and dykes of feldspar porphyry.

12.1 DWYKA AND PRINCE ALBERT FORMATIONS

The Prince Albert Formation, forming an outcrop that is too small to be shown on the map, occurs next to the dolerite on the eastern flank of the Okotjize Fold and made up of grey bedded shale with a few thin beds of limestone and several large carbonate concretions.

The outcrop of Dwyka occurs between Otjomkona and Okongwe and consists of tillite which contains boulders of granite, schist and dolomite. The matrix of the tillite is argillaceous but contains a considerable amount of calcite and a high proportion of grit-sized material.

12.2 OMINGONDE FORMATION

The name Omingonde was proposed by Keyser (1973) for the red mudstones, grits, shales and sandstones that occur in the Otjiwarongo District and were named the Lower Etjo Beds by Gevers (1936).

Rocks of the Omingonde Formation make up the lower portion of the Karoo Sequence in the Otjongundu Plateau and also occur sandwiched between the overlying feldspar-porphyry silk Small outcrops are present on the eastern and northern margins of the Okenyenya Complex and one rests on top of the rocks of this body. Five kilometres west of the Otjohorongo Granite, Omingonde rocks are preserved in a small downfaulted trough and west of the Otjozondjou village a very small, outcrop is overthrust by Kuiseb schist. The sedimentary rocks of the Otjongundu Plateau have been protected from erosion by the feldspar-porphyry capping and the uppermost beds occur more than 350m above the surrounding plain. The sedimentary rocks on the margins of the Okenyenya Complex are morphologically prominent. This can be ascribed in part to their proximity to the weather-resistant igneous rocks and in part to the effect of baking by this intrusion. Outcrops farther east are flat-lying and only very poorly exposed.

The Omingonde rocks are composed of massive mudstone with intercalations of poorly bedded grit and conglomerate. The sedimentary rocks of the Otjongundu Plateau are both red and white in colour but farther east they are all red. Most of the pebbles and the grit-sized fragments have been locally derived. In the deposits forming the Otjongundu Plateau, rounded and broken potash-feldspar phenocrysts from the underlying Salem granite are numerous and there are many pebbles of Kuiseb schist from the metamorphic aureole just to the north.

The sequence that is the most complete of the Omingonde Formation in the area occurs on the western edge of the Otjongundu Plateau below the feldspar-porphyry sills. The beds are listed from top to bottom in table 12.1.

Table 12.1 SEQUENCE OF THE OMINGONDE FORMATION

Lithology	m *Thick*
Massive fine-grained to slightly gritty mudstone...	50
White grits with subordinate red- and pink-coloured zones, a few thin conglomeratic bands	120
White grits..................................	40
Unsorted gritty conglomerate, pebbles up to 30 cm in diameter and composed of quartz, schist and granite.................................	3
White, pink and red pebbly grits. Uncomformable contact with Salem granite...................	20
	233

12.3 FELDSPAR-PORPHYRY SILLS

The Karoo feldspar-porphyry sills are limited to the Otjongundu Plateau. In the southern portion of the Plateau there are scarcely any interbedded sedimentary rocks between the sills, but in the northern half sills and sedimentary rock alternate quite regularly, despite the fact that layers of the latter are usually quite thin. For the most part the sills are flat-lying but a few in the north are inclined at angles of up to 45°. In this area crosscutting dykes of feldspar porphyry are numerous in the Kuiseb schist arid the Salem granite, and some intersect the sills themselves. Two of these dykes disappear into the base of sills and are clearly feeders. It is probable that all the dykes served the same purpose.

Two 30-cm-thick sills on the southern flank of Okenyenya have been, baked with the sedimentary rocks to a grey colour by the intrusion of the Okenyenya Complex. It is thus evident that the feldspar porphyry is older than the Complex.

In vertical sequence a maximum number of eight sills has been found. These are commonly light-buff or light-red in colour but white and light-purple sills are also present. No flow banding was observed. Quantities of feldspar phenocrysts vary considerably from sill to sill. They are generally all between 1 and 2 mm in size and white or light-buff in colour. A few small euhedral to anhedral phenocrysts of ore are present and two sills also carry a few small quartz phenocrysts. Small cavities are fairly common and are, generally filled with powdery red or yellow iron oxide.

Thin sections reveal porphyritic to glomeroporphyritic textures. Alkali-feldspar phenocrysts are most common, followed by plagioclase and then ,quartz (table 12.2), In most cases the groundmass is very fine grained but often fine graphic intergrowths can be recognised. These are concentrated around quartz phenocrysts. A little fine-grained muscovite is present and fluorite occurs in some cavities. All feldspar is very strongly clouded.

Most feeder dykes are very similar in appearance to the sills but there are a few which are trachytic and only slightly porphyritic. A sample of the latter type of dyke has a decussate texture and is composed mainly of small twinned crystals of alkali feldspar but it also contains about 10 per cent intergranular quartz, 10 per cent highly oxidised iron ore and a little calcite.

Table 12.2 PROPORTIONS OF PHENOCRYSTS PRESENT IN THE KAROO FELDSPAR-PORPHYRY SILLS OF OTJONGUNDU PLATEAU

Sample no.	RM 622	RM 623	RM 880	RM 882
Phenocrysts:				
Quartz............	—	—	0,3	1,0
Alkali feldspar......	9,0	16,0	9,0	17,0
Plagioclase.........	1,0	4,0	0,5	1,0
Groundmass:				
Quartz............	89,0	24,0	90,2	81,0
Feldspar...........		54,0		
Ore...............		3,0		

12.3.1 Geochemistry

Samples from two of the feldspar-porphyry sills and one from a non-porphyritic feeder dyke have been analysed. The results are presented in table 12.3 and cation per cents and mesonorms, are given in table 12.3 (a).

The feldspar-porphyry sills are alkaline and compare well with Nockolds's (1954) average alkali rhyolite. Differences that are present are only slight. In the sills more of the iron is in the trivalent state. One sample (RM 622) contains more MgO and both sills contain a little less CaO than Nockolds's average. In the Karoo samples there is considerably more K_2O than Na_2O whereas in the Nockolds's average the K_2O/Na_2O ratio is only a little greater than one.

The trachytic feeder dyke is peralkaline and compares well with Nockolds's (1954) average peralkaline trachyte. Nearly all the iron in the sample is present as ferric iron whereas in the Nockolds's average about 40 per cent of the iron is in the form of FeO. The sample also contains a little less MgO and CaO. The high loss on ignition can be ascribed to loss of CO_2 from calcite which has been found in thin section.

A consideration of the relative proportions of trace elements present in the samples reveals that the porphyry sills contain more Rb and Ba and less Sr than the feeder dyke. The K/Rb and K/Ba ratios emphasise the smaller quantities of Rb and Ba present in the trachyte.

12.4 DOLERITE

Dolerites of Karoo age occur either in the form of dykes or as fairly thick sills. The dykes can be found scattered throughout the area but are particularly numerous in the region between the Okenyenya Complex and the Otjohorongo Granite, where most are preferentially orientated in north-north-easterly or east-south-easterly directions. Two large sills occur just west of the Otjongundu Plateau and remnants of sills have also been found near the southern tip of the Okotjize Fold, overlying the Naauwpoort metavolcanics of the Ais Dome and near the western boundary of Sorris-Sorris 186. Sills and dykes are intrusive into the Naauwpoort rocks, the Salem granite and the Kuiseb schist. The sill with the largest areal outcrop, occurring immediately to the north and west of the Otjongundu village is 30 m thick and still supports a few remnants of Salem granite. The other large sill, just to the south, is basin-shaped and the northern and southern edges dip inwards at angles of about 45°. Although it has not been possible to determine the dip of the western edge, it does appear to be more steeply inclined. The outcrop width of this edge is 350 m.

Table 12.3 (a) CATION PER CENTS AND MESONORMS OF KAROO SEQUENCE FELDSPAR - PORPHYRY SILLS AND FEEDER DYKE

	Feldspar-porphyry sills		Feeder dyke
Sample no.	RM 622	RM 623	RM 614
Cation per cent:			
Si	68,57	70,02	57,51
Ti	0,12	0,12	0,17
Al	14,54	14,58	18,56
Fe^{3+}	1,40	1,63	3,78
Fe^{2+}	0,32	0,25	0,11
Mn	0,08	0,09	0,08
Mg	1,05	0,19	0,28
Ca	0,46	0,16	1,33
Na	6,50	5,90	8,34
K	6,99	7,09	9,82
P	0,04	0,03	0,07
Mesonorm:			
Quartz	27,4	31,0	1,3
Orthoclase	32,6	31,8	49,1
Albite	32,5	29,5	41,7
Anorthite	1,5	—	1,0
Muscovite	1,0	3,2	—
Biotite	3,0	0,7	—
Diopside	—	—	1,4
Wollastonite	—	—	1,0
Sphene	0,4	0,4	0,5
Magnetite	1,0	0,7	0,3
Hematite	0,8	1,2	3,6
Apatite	0,1	0,1	0,2

Table 12.3 (a) CATION PER CENTS AND MESONORMS OF KAROO SEQUENCE FELDSPAR - PORPHYRY SILLS AND FEEDER DYKE

	Feldspar-porphyry sills		Feeder dyke
Sample no.	RM 622	RM 623	RM 614
Cation per cent:			
Si	68,57	70,02	57,51
Ti	0,12	0,12	0,17
Al	14,54	14,58	18,56
Fe^{3+}	1,40	1,63	3,78
Fe^{2+}	0,32	0,25	0,11
Mn	0,08	0,09	0,08
Mg	1,05	0,19	0,28
Ca	0,46	0,16	1,33
Na	6,50	5,90	8,34
K	6,99	7,09	9,82
P	0,04	0,03	0,07
Mesonorm:			
Quartz	27,4	31,0	1,3
Orthoclase	32,6	31,8	49,1
Albite	32,5	29,5	41,7
Anorthite	1,5	—	1,0
Muscovite	1,0	3,2	—
Biotite	3,0	0,7	—
Diopside	—	—	1,4
Wollastonite	—	—	1,0
Sphene	0,4	0,4	0,5
Magnetite	1,0	0,7	0,3
Hematite	0,8	1,2	3,6
Apatite	0,1	0,1	0,2

Most of the dykes are fine to medium grained with intergranular to slightly subophitic textures. A few dykes are slightly porphyritic. Mineralogically the dykes have the composition either of dolerite or of olivine dolerite. Plagioclase is zoned and usually varies from An_{47} to An_{71}, Where olivine is abundant, the plagioclase is more calcic and varies from An_{72} to An_{80} and the composition is thus eucritic. Clino-pyroxene has the faint purplish colour of titanaugite and has optic angles of between 46° and 49°. Measurements of 2Vx of olivine indicate compositions of between Fo_{10} and Fo_{40}. The olivines highest in Mg occur in the eucritic dykes. In the slightly porphyritic dykes olivine forms small euhedral phenocrysts.

All the sills are mineralogically very similar. A sequence of samples from the thick sill at Okondomba village did not show any compositional changes which could be attributed to differentiation. A chill phase is developed along all margins. Apart from these fine-grained margins, the sills have a characteristic mottled appearance produced by numerous large almost circular augite phenocrysts which can be as much as 8 mm in diameter. In thin section the augite ophitically encloses numerous medium- to fine-grained plagioclase laths. Olivine is a minor constituent and accessory amounts of ore and secondary very light-green serpentine are present. Plagioclase is zoned and varies in composition from An_{57} in the cores of crystals to An_{47} at the edges. The 2V of augite varies between 43° and 50°, the lower angles indicating a slightly subcalcic augite (Deer, Howie and Zussman 1962). Modes are given in table 12.4.

Table 12.4 MODES OF KAROO DOLERITE SILLS

Sample no.	RM 363	RM 620
Plagioclase........	55,20	59,20
Core...........	An_{87}	An_{60}
Margin.........	An_{47}	An_{47}
Augite............	27,80	26,50
2Vz.............	47° – 50°	43°
Olivine...........	13,70	11,40
Ore..............	2,40	1,60
Serpentine........	1,0	0,8

Sample localities: RM 363—1 km north of Otjongundu village.
RM 620—Okondomba village.

13. POST-KAROO INTRUSIVE ROCKS

13.1 OKENYENYA COMPLEX

The Okenyenya (Okonjeje) Complex is a differentiated sequence of basic rocks with both tholeiitic and alkaline affinities and has been described by Simpson (1954).

13.2 OTJOHORONGO GRANITE

The Otjohorongo Granite, a zoned stock of alkali granite and granite porphyry, is situated in the southeastern corner of the area. Associated with the stock are ring dykes, cone sheets and linear dykes of quartz porphyry and aplite.

13 .2. 1 Granite stock

The Otjohorongo Granite stock is an almost circular intrusion which occurs very close to the contact between the Kuiseb schist and the Salem granite. It consists of an outer zone of coarse-grained yellowish granite followed by granite porphyry. This in turn grades into medium-grained granite with only very few phenocrysts near the centre of the body.

The stock has mechanically forced its way into the schist and as a result the foliation in the schist is now highly contorted. In the metamorphic aureole which has a maximum width of 1,5 km on the northern edge (fig. 9. 1), the schist is very fine-grained right up to the contact and consists largely of quartz and muscovite. Only in the sample taken 3 m from the granite is there a slight increase in the grain size of the muscovite. There is a complete lack of spotting in the schist.

The outer coarse-grained granite zone shows no signs of chilling at its contact with the schist and contains only very rare schist inclusions. It has a maximum width of approximately 1,5 km but is actually quite discontinuous, for it is intensely dissected by the later granite porphyry. Most bodies of the latter have a dyke-like form and vary tremendously in width from a few metres to as much as 250 m. Contacts between coarse-grained granite and granite porphyry are often preferentially orientated in an east-south-easterly direction suggesting some control of intrusion by jointing. Many of the larger granite-porphyry dykes cut right across the outer coarse-grained zone and are in direct contact with the schist. These show no signs of chilling at the contact. The intrusive bodies of granite porphyry are too numerous and too variable in size to map on a small scale, and large-scale mapping was beyond the scope of this study.

Thus, the outer margin of the granite porphyry is most irregular and jagged as a result of the numerous offshoots that intrude the coarse-grained granite. In the outer portions of this zone phenocrysts are numerous but they gradually decrease in number towards the centre and eventually the granite porphyry grades into the zone of medium-grained granite which contains very few phenocrysts. This zone is centrally situated in the stock and is about 500 m across. Its limits are, however, difficult to define because of the gradation between it and the granite porphyry. A few thin irregularly orientated dykes of the medium-grained granite cut the rocks of the two outer zones. The latter are also cut by a few thin aplite dykes. Modes of samples from each zone are presented in table 13.1.

Table 13.1 MODES OF SAMPLES FROM OTJOHORONGO GRANITE STOCK

	Marginal coarse-grained granite			Granite porphyry		Central medium-grained granite	Aplite dyke
Sample no.	RM 37	RM 610	RM 611	RM 357	RM 896	RM 900	RM 897
Quartz....................	34	35	43	31	38	41	43
Potash feldspar............	37	40	31	38	43	36	43
Plagioclase................	24	19	22	28	16	21	10
Biotite....................	Tr	Tr	—	2	2	1	4
Muscovite................	4	5	3	1	1	Tr	Tr
Ore......................	1	1	1	Tr	—	Tr	Tr
Accessory minerals.........	Schorl	Fluorite Zircon Schorl	Fluorite Zircon Schorl	Zircon	Zircon	Fluorite Zircon	—

The proportions of potash feldspar and plagioclase in the coarse-grained granite vary quite considerably and the minerological composition of some specimens corresponds to that of an adamellite. Quartz and very coarsely perthitic potash feldspar are the main components. The potash feldspar (2V =58°-65°) is generally not twinned but in one slide (RM 610) tiny cross-hatched patches are present in a few crystals. Plagioclase is generally much smaller than orthoclase, though a few crystals 7 mm long are present. Apart from small slightly saussuritised patches in the centres of some of the larger crystals, the plagioclase is completely fresh and has the composition of pure albite. Very minor quantities of muscovite are present and there are accessory amounts of brown biotite, ore, schorl, zircon and fluorite. Colourless and purple varieties of the last mineral are present.

Sparsely scattered throughout the coarse-grained granite are small drusy pegmatitic patches usually not more than 15 cm in diameter. These contain mainly quartz and schorl but a little potash feldspar is also present and, very rarely, light-blue crystals of poor-quality aquamarine. There are also rare dykes not more than 20 m long composed entirely of intergrown quartz and schorl.

The groundmass of the granite porphyry is medium grained. Quartz and potash-feldspar phenocrysts with respective maximum sizes of 7 mm and 8 mm make up about 20 per cent of the rock. The average size of plagioclase crystals is less than 1 mm and the largest crystals are not more than 3 mm in length. The groundmass potash feldspar is non-perthitic but the phenocrysts (2V = 55°-68°) are coarsely perthitic and similar in all respects to the perthite in the coarse-grained granite, even down to the small inclusions of plagioclase and quartz. The composition of the plagioclase varies from An_o to An_4. A few of the larger plagioclase crystals are slightly saussuritised. Accessory constituents are brown biotite, muscovite, ore and zircon.

Potash feldspar (2V=57° - 69°) in the medium-grained granite is finely perthitic. Most of the plagioclase is slightly saussuritised and varies in composition from An_2 to An_6. Dark greyish-green biotite is a very minor constituent and there are accessory amounts of ore, muscovite, zircon and fluorite.

Samples from the aplite dykes are very similar in most respects to the medium-grained granite but are a little finer in grain size. Potash feldspar (2V = 61 °-64°) is finely perthitic. The composition of plagioclase varies from An_1 to An_6. The aplite contains noticeably more biotite than any of the other rock types.

The differences in mineralogical composition of the rocks from the various zones are only slight. The An content of plagioclase increases very slightly towards the centre. Muscovite is most abundant in the outer coarse-grained granite and decreases in amount towards the centre. This decrease is accompanied by an increase in the amount of biotite which changes in colour from brown to green. Schorl appears to be limited to the outer coarse-grained granite as are the small pegmatitic druses.

13.2.2 Ring dykes

The quartz-porphyry ring dykes form a curved outcrop just to the south and east of the Otjohorongo Granite stock. They are intrusive into the Kuiseb schist and the diorite of the Salem Suite.

A total of 17 dykes occur north of Otjozondjou, but these gradually decrease in number towards the east. Most are thick (30 m - 40 m) and they are fairly closely spaced so that it has not been possible to show the dykes separately where there are many of them. In the west most of the dykes end abruptly against the post-Karoo thrust. A few occur in the schist west of the thrust. Details of the 17 dykes occurring north of Otjozondjou are recorded in sequence from south to north in table 13.2.

Table 13.2 DESCRIPTION OF 17 DYKES OCCURRING NORTH OF OTJOZONDIOU

		m *thick*
(1)	Light-pink porphyry. Quartz phenocrysts - 2 mm, pink feldspar phenocrysts - up to 8 mm. Slight tendency to be glomeroporphyritic. Small schorl patches	7
(2)	Light pinkish-buff porphyry. Very similar to above, but has more phenocrysts which are slightly larger	40
(3)	Buff-coloured porphyry. Numerous quartz and pink feldspar phenocrysts, each up to 3 mm across. A few schorl patches. Geochemical sample RM 608	40
(4)	Pink quartz-feldspar porphyry. Maximum diameters, quartz - 3 mm, pink feldspar - 1 cm. Slight tendency to be glomeroporphyritic. A few small schorl patches	40
(5)	Pink quartz-feldspar porphyry with small phenocrysts. Average size of phenocrysts, quartz - 1 mm, feldspar - 2 mm. A few small schorl patches. Contains thin isolated breccia zones which run parallel to the strike of the dyke, but which are not more than 15 m long. Breccia fragments welded together or cemented by chert-like material	30
(6)	Medium-grained aplitic dyke. Highly fractured and criss-crossed by numerous very thin schorl veinlets	2
(7)	Buff quartz-feldspar porphyry. Maximum size of phenocrysts, quartz - 3 mm, pink feldspar - 5 mm. A few small schorl patches	5
(8)	Buff quartz-feldspar porphyry. Very similar to above but with slightly fewer phenocrysts. No schorl	3
(9)	Medium-grained aplitic dyke even more fractured and veined by schorl than the previous aplitic dyke. Contains small pegmatitic patches in places with pinkish perthite crystals up to 15 cm long which are accompanied by quartz, a little plagioclase and accessory schorl. The dyke contains a 30-m-long, 5-cm-wide breccia zone made up of a few small angular fragments of aplite set in an abundant matrix of fine-grained schorl	40
(10)	Pinkish-buff quartz-feldspar porphyry. Maximum size of phenocrysts, quartz - 3 mm, pinkish feldspar - 4 mm. Matrix very fine grained. Several schorl patches	7
(11)	Pinkish-buff quartz-feldspar porphyry. Maximum size of phenocrysts, quartz - 3 mm, pink feldspar - 6 mm. Slight tendency to be glomeroporphyritic. Groundmass is finer grained near the edge of the dyke. Numerous small schorl patches at edge of dykes, a few large patches in centre	40
(12)	Quartz-feldspar porphyry, brown in colour on weathered surfaces, grey on fresh surfaces. Maximum size of phenocrysts, quartz - 3 mm, feldspar - 1 cm. Fresh feldspar phenocrysts are white in colour; on weathered surfaces many can be seen to contain small plagioclase crystals in their cores. Geochemical sample RM 609	60
(13)	Fine-grained aplitic dyke, similar to the others but not fractured and has no schorl veinlets	4
(14)	Buff quartz-feldspar porphyry. Maximum size of phenocrysts, quartz - 3 mm, buff feldspar - 4 mm	20
(15)	Medium-grained aplitic dyke with abundant biotite	4
(16)	Buff quartz-feldspar porphyry. Phenocryst diameters, quartz - 2 mm, feldspar - 4 mm	5
(17)	Aplitic dyke that is slightly porphyritic. Contains many small schorl patches. Has pegmatitic edge and many pegmatitic patches in the centre. Contains partially digested schist xenoliths	30

The majority of the ring dykes are composed of quartz-felspar porphyry, the remainder being made up of aplite. On the basis of petrographic evidence the latter can be subdivided into microcline-bearing dykes and dykes that carry only untwinned potash feldspar.

In the porphyry dykes the most abundant mineral is quartz, followed by clouded perthitic alkali feldspar (2V=59°-74°) and plagioclase (table 13.3). A few of the quartz phenocrysts are euhedral, but most are rounded and embayed as a result of resorption. Alkali-feldspar phenocrysts are both euhedral and anhedral. A few are slightly rounded as a result of resorption. Plagioclase phenocrysts (An_0-An_5) are generally small and usually subhedral and in most samples they tend to occur in glomeroporphyritic clusters. Crystals are fairly strongly saussuritised indicating an original more calcic composition.

Table 13.3 PROPORTIONS OF PHENOCRYSTS IN THE QUARTZ-FELDSPAR PORPHYRY RING DYKES ASSOCIATED WITH THE OTJOHORONGO GRANITE

Sample no.	RM 608	RM 609	RM 841
Phenocrysts:			
Quartz	7	13	18
Perthite	14	12	7
Plagioclase	3	—	3
Groundmass	76	75	72

The groundmass of the porphyry dykes is composed of a fine-grained granular mass of quartz and clouded feldspar. Within this, fine graphic intergrowths are quite numerous. Many of these are concentrated around perthite phenocrysts and some actually grow from the planes of these crystals. The feldspar of the intergrowths is not necessarily optically continuous with the central feldspar phenocryst. Muscovite, brown biotite, schorl and ore are accessory constituents of the groundmass. In some specimens small cavities contain carbonate, euhedral quartz crystals, fluorite and muscovite and in one dyke there are also small patches of devitrified glass containing micro-spherulites.

The cementing material of all the breccias in the porphyry dykes is chert. In one sample this is accompanied by considerable quantities of colourless fluorite.

Modes of the aplitic ring dykes are presented in table 13.4. In thin section the texture of the aplitic ring dykes is typically granitic. Two of the dykes carrying untwinned potash feldspar have very similar mineralogies (RM 857, RM 861). These contain almost equal quantities of potash feldspar (2V = 52°-59°) and plagioclase. The latter mineral varies from An_0 to An_3 in composition but all the grains are saussuritised. In contrast, the biotitic aplite dyke (RM 858) contains much more plagioclase than potash feldspar (2V =61° - 64°), the former being fresh and having a composition range of An_{24} to An2s’

The remaining aplitic dykes are very rich in microcline (RM 846). This mineral has a very well-developed cross-hatching and a 2V angle which varies between 78° and 81°. Plagioclase is slightly saussuritised and varies from An_0 to An_2 in composition. A few plagioclase crystals contain small inclusions of schorl. These dykes are criss-crossed by thin schorl veinlets. In thin section the veinlets are found to contain a few small euhedral quartz crystals. A section of the schorl-cemented breccia contains fragments of aplite, quartz, microcline and plagioclase of all sizes. The schorl is in the form of minute crystals.

Table 13.4 MODES OF APLITIC RING DYKES ASSOCIATED WITH OTJOHORONGO GRANITE

	Dykes with untwinned potash feldspar			Microcline-bearing dyke
Sample no.	RM 857	RM 858	RM 861	RM 846
Quartz	28	31	29	29
Untwinned potash feldspar	36	19	33	—
Microcline	—	—	—	49
Plagioclase	32	42	32	19
Biotite	—	8	—	—
Muscovite	4	—	1	—
Schorl	Tr	—	4	3
Accessory minerals	—	Zircon Apatite Ore	—	Zircon Ore

13.2.3 Cone sheets

Quartz-feldspar porphyry cone sheets form a 11-km-long slightly curved outcrop 7 km south of Otjozondjou. As contacts are covered by scree, it has not been possible to determine their dip accurately, but an angle of about 60° is suggested by the form of some outcrops. Five single dykes and two highly branched dykes are present.

The most abundant porphyritic mineral is pink potash feldspar followed by quartz and then plagioclase (table 13.5). Both euhedral and anhedral potash-feldspar phenocrysts are present, all strongly sericitised and clouded. In some samples large cavities in the phenocrysts are filled with carbonate. Plagioclase crystals are generally subhedral. All are strongly saussuritised and now have the composition of pure albite. A few euhedral quartz phenocrysts are present but most have been rounded and embayed by resorption.

Table 13.5 PROPORTIONS OF PHENOCRYSTS PRESENT IN THE QUARTZ-FELDSPAR PORPHYRY CONE SHEETS ASSOCIATED WITH OTJOHORONGO GRANITE

Sample no.	RM 612	RM 613	RM 879
Phenocrysts:			
Quartz	5	9	6
Potash feldspar	15	13	13
Plagioclase	4	3	6
Groundmass	76	75	75

The groundmass is fine grained, pink, red or dark brown in colour and contains abundant graphic intergrowths. In some samples small subhedral quartz and feldspar crystals are also present. Muscovite occurs in some samples and dark-green biotite in others; in most a few relatively large zircon crystals have been observed. A little fluorite and calcite occur in cavities and one sample also contains a little devitrified glass. Another sample contains strongly chloritised remnants of what might have been aegirine.

13.2.4 Linear dykes

The linear quartz-porphyry dykes associated with the Otjohorongo Granite are both red and buff in colour and intrude the country rock surrounding the stock. Many of the smaller dykes are not shown on the map and a few of them extend from the stock itself. There is a well-developed preferential orientation of the dykes in a north-north-easterly direction.

Phenocrysts are mainly of quartz and potash feldspar but a few large plagioclase crystals are also present. Potash-feldspar phenocrysts are the largest and are cloudy due to alteration. Quartz phenocrysts can be euhedral but generally have undergone varying degrees of resorption. Plagioclase is subhedral and saussuritised. The groundmass of the dykes is made up of very fine-grained quartz and feldspar. Accessory quantities of muscovite, brown biotite and schorl are usually present and one sample also contains small amounts of fluorite and topaz.

13.2.5 Geochemistry

Two samples of coarse-grained granite, two of the ring dykes and two of the cone sheets have been analysed. Results are presented in table 13.5 (a) and cation percentages and mesonorms are given in table 13.5 (b).

All the rocks are alkaline and compare fairly well with Nockolds's (1954) average alkali granite. In all but one sample (RM 613) there is more FeO than Fe_2O_3, MgO is variable but is comparable with MgO in Nockolds's average. Most of the samples contain a little more CaO than Nockolds's average.

The two samples from the cone sheets both contain comparable quantities of Rb, Ba, Sr and Cu. Although the K/Rb ratios of these samples are within the "normal" range of between 150 and 300 (Taylor 1965), they are on the low side indicating a relatively high proportion of Rb. Concentrations of Ba are less than half the average of 660 ppm for granite (Taylor 1965, p. 152) and Sr is very low compared to the average Sr content of 285 ppm for granite (Taylor 1965). Cu is double the average of 10 ppm found in granite (Taylor 1965, p. 177).

The K/Rb, K/Ba and Ba/Rb ratios of the ring-dyke samples indicate that there is an increase in Rb and a decrease in Ba relative to the cone sheets. There is a significant decrease in the amount of Sr but Cu remains more or less the same. One of the dykes (RM 609) contains more Rb and much less Ba and Sr than the other (RM 608) which clearly indicates that the former is more highly differentiated than the latter. This is also shown by the low K/Rb ratio and high K/Ba ratio of RM 609.

The coarse-grained granite (samples RM 610' RM 611) contains large amounts of Rb and only very little Ba and Sr. The very low K/Rb and Ba/Rb ratios indicate that it is very highly differentiated.

13.2.6 Sequence of events

The foregoing field and geochemical evidence indicate that the following was the probable sequence of events:

(1) Incomplete cone-shaped fractures formed as a result of initial explosive activity and rhyolitic magma containing about 25 per cent of solids intruded along them.

(2) A second explosive phase formed incomplete ring fractures fairly near the curvature of the cone sheets. Magma intrusion along these followed. The brecciated quartz porphyries, the variable mineralogy of the ring dykes and the difference in the trace-element geochemistry of the two analysed ring-dyke samples indicate several periods of explosive activity and intrusion.

(3) Intrusion of the coarse-grained zone of the granite stock took place subsequent to the formation of the quartz-feldspar-porphyry ring dykes. Because of the lack of chilling along the contact with the schist, this material must have contained only just enough liquid to enable movement to take place.

(4) Subsequent intrusion of the granite porphyry caused the diameter of the stock to enlarge. This resulted in the formation of expansion joints in the coarse-grained granite which became filled with porphyry granite as intrusion continued. Since no sharp contact exists between the granite porphyry and the medium-grained granite, it seems probable that the latter represents the final phase of the granite-porphyry intrusion. Some of the linear dykes are associated with the intrusion of the granitic rocks, but there are several which are very similar in appearance to the ring dykes and cone sheets and it is probable that the linear dykes formed during each intrusive stage. It is difficult to say just where the aplitic ring dykes belong in the intrusive cycle, but the large amount of the volatile component, Be, associated with the microcline-bearing dykes, suggests that they formed at a very late stage. The high biotite and plagioclase content of the one aplite dyke might have resulted from contamination of the magma by the Kuiseb schist. Fairly large-time intervals between each intrusive phase in order to enable differentiation to change the trace-element concentrations in the magma so significantly were bound to occur.

It is extremely difficult to pick up changes resulting from differentiation in the fine-grained dyke rocks and even in the granitic rocks significant mineralogical changes cannot be detected. The number of analyses carried out do not provide a complete picture of the associations and the sequence of events. There thus remains ample scope for further research on the stock and its associated dykes.

13.3 KWAGGASPAN CARBONATITE

The Kwaggaspan Carbonatite occurs 7 km northeast of Omauzongaka where it intrudes the Kuiseb schist. It consists of five small plugs, two of carbonatite, one of a quartz-hematite-muscovite rock and two of very fine-grained iron oxide and silica. The plugs are aligned along a 1,3-km-long gently curving east-west orientated breccia zone in the schist but are confined to the western 0,6 km of this zone. Most of the brecciated schist is intruded by thin veinlets of sövitic carbonatite.

The westernmost plug with a diameter of 150 m is the largest and consists mainly of sövitic carbonatite with abundant disseminated hematite. In the centre of the plug there are large xenoliths several metres in diameter of banded ironstone, dolomite and schist, all more or less brecciated. Near the north-western edge is a body of high-grade hematite ore 10 m in diameter.

The only sign of fenitisation that could be found was the growth of green pyriboles in a limited number of small schist outcrops on the western edge of the westernmost plug.

Table 13.5 (a) ANALYSES OF SAMPLES OF OTJOHORONGO GRANITE AND ASSOCIATED QUARTZPORPHYRY RING DYKES AND CONE SHEETS

	Coarse-grained granite		Quartz-porphyry ring dykes		Quartz-porphyry cone sheets		
Sample no.	RM 610	RM 611	RM 608	RM 609	RM 612	RM 613	(a)
SiO_2	75,82	75,52	75,32	76,46	72,24	72,07	73,86
TiO_2	0,05	0,06	0,06	0,09	0,21	0,19	0,20
Al_2O_3	12,22	12,41	12,39	11,52	12,90	12,55	13,75
Fe_2O_3	0,53	0,45	0,26	0,07	0,51	1,59	0,78
FeO	0,80	0,87	0,42	1,59	2,02	0,65	1,13
MnO	0,04	0,03	0,01	0,02	0,05	0,03	0,05
MgO	0,18	0,12	0,09	0,15	0,24	0,42	0,26
CaO	0,41	0,69	1,17	0,80	1,10	1,21	0,72
Na_2O	3,82	3,48	3,96	3,22	3,10	2,72	3,51
K_2O	5,17	4,77	4,66	4,58	5,69	6,27	5,13
P_2O_5	0,04	0,03	0,02	0,03	0,04	0,04	0,14
l.o.i.	0,68	0,75	0,93	0,89	1,19	1,69	0,47†
H_2O^-	0,12	0,10	0,22	0,14	0,30	0,20	—
Totals	99,88	99,28	99,51	99,56	99,59	99,63	—
Trace elements, ppm:							
Rb	539	537	279	344	255	283	—
Ba	45	47	216	45	294	274	—
Sr	13	9	34	9	65	47	—
Cu	19	19	22	28	23	20	—
Inter-element ratios:							
(Na+K)/Al	1,10	0,99	1,04	1,03	1,02	1,08	0,94
K/Rb	80	74	139	110	185	184	—
K/Ba	954	842	179	844	160	190	—
Ba/Rb	0,08	0,09	0,77	0,13	1,16	0,97	—

(a) = Nockolds's (1954) average alkali granite.
† = H_2O^+
Analyst: Geochemistry Department, University of Cape Town.

Table 13.5 (b) CATION PER CENTS AND MESONORMS OF ANALYSED SAMPLES OF OTJOHORONGO GRANITE AND ASSOCIATED QUARTZ-PORPHYRY RING DYKES AND CONE SHEETS

	Coarse-grained granite		Quartz-porphyry ring dykes		Quartz-porphyry cone sheets	
Sample no.	RM 610	RM 611	RM 608	RM 609	RM 612	RM 613
Cation per cent:						
Si	71,47	71,88	71,36	73,03	69,09	69,30
Ti	0,03	0,05	0,05	0,07	0,16	0,14
Al	13,59	13,93	13,84	12,98	14,55	14,23
Fe^{3+}	0,38	0,33	0,19	0,06	0,37	1,16
Fe^{2+}	0,64	0,70	0,34	1,28	0,62	0,53
Mn	0,03	0,03	0,01	0,02	0,05	0,03
Mg	0,26	0,18	0,13	0,22	0,35	0,61
Ca	0,42	0,71	1,19	0,82	1,13	1,25
Na	6,99	6,43	7,28	5,97	5,75	5,08
K	6,22	5,80	5,64	5,59	6,95	7,70
P	0,04	0,03	0,02	0,03	0,04	0,04
Mesonorm:						
Quartz	30,87	33,95	30,63	36,90	29,02	28,36
Orthoclase	30,51	27,28	28,17	25,45	31,69	38,46
Albite	34,92	32,12	36,38	29,82	28,75	25,36
Anorthite	0,96	3,11	2,34	3,57	4,62	3,67
Muscovite	—	0,96	—	—	—	—
Biotite	0,93	1,94	—	3,94	4,85	—
Actinolite	1,12	—	—	—	—	1,52
Diopside	—	—	1,51	—	—	0,49
Wollastonite	—	—	0,56	—	—	—
Sphene	0,07	0,13	0,13	0,20	0,46	0,42
Magnetite	0,57	0,49	0,28	0,08	0,56	1,57
Hematite	—	—	—	—	—	0,11
Apatite	0,09	0,07	0,05	0,07	0,09	0,09

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GEOLOGIE VAN 'N DEEL VAN SENTRAAL-DAMARALAND, SUIDWES-AFRIKA/NAMIBIË

1. INLEIDING

Die gebied wat omtrent 70 km noordwes van Omaruru, Suidwes-Afrika, geleë is, is gedurende 1969-1970 gekarteer (fig. 1.1). Dit beslaan 'n oppervlakte van sowat 6 500 km^2 en sluit blaaie 2014D en 2015C (en klein gedeeltes van blaaie 2015A en 2015C) in.

2. ALGEMENE STRATIGRAFIE

Die oudste gesteentes, naamlik gneis en kwartsiet van die Kompleks Huab, kom noord van die Summasberge voor. Dit word diskordant bedek deur die Opeenvolging Damara met vulkaniese suurgesteentes van die Formasie Naauwpoort aan die basis, gevolg deur karbonaatgesteentes en skis van die Groep Swakop. Die kontak tussen die Naauwpoort- en Swakopgesteente is plek-plek effens diskordant, maar noord van die Summasberge is die twee eenhede tussengelaag en die kontak dus konkordant. Skis van die Groep Mulden is jonger as die Swakopgesteentes maar ouer as die na-tektoniese Suite Salem en Sorris-Sorris-Graniet. Laasgenoemde is die produk van hoëgraadse metamorfose van die Naauwpoortrioliet. Gesteentes van die Groep Karoo lê diskordant op Damaragesteentes en die Salemgraniet. Daar is drie na-Karoointrusies, naamlik die basiese Kompleks Okenyenya, die suur Otjohorongo-Graniet en die K waggaspan- Karbonatiet.

Die vorige stratigrafiese interpretasie van die gebied (Geologiese Kaart van Suidwes-Afrika 1963) word in figuur 2.1 met die van die huidige ondersoek vergelyk.

3. KOMPLEKS HUAB

Die gneis is middelkorrelrig, adamellities en het 'n goedontwikkelde foliasie. Die tussengelaagde kwartsiet het 'n granoblastiese tekstuur en bevat redelik baiegoedgeorienteerde muskoviet. Dit het 'n ouderdom van 1 700 - 1 800 Ma (Burger, Clifford en Miller 1976).

4. FORMASIE NAAUWPOORT

4.1 STRATIGRAFIE

Die Formasie Naauwpoort wat net uit vulkaniese gesteentes bestaan, word onderverdeel in 'n onderste en boonste eenheid.

4.1.1 Formasie Onder-Naauwpoort

Omdat die basis van die suksessie nie blootgestel is nie, word aanvaar dat die dikte van laasgenoemde meer as 6 600 m is. Die Formasie bestaan byna geheel en al uit suur asvloeie (ignimbriete) wat meer fynkorrelrig word na die suide toe (fig. 4.1, 4.2, 4.3 en 4.4). Vloeie met blokke en baie ondergeskikte lawa is tot die Summasberge beperk (fig. 4.3 en 4.5). Onder die invloed van die Damarametamorfose het hierdie gesteentes in die Aiskoepel en in die grootste deel van die Mittenplooi 'n arkoosagtige voorkoms.

4.1.2 Formasie Bo-Naauwpoort

Hierdie gesteentes lê konkordant op die Onder-Naauwpoortgesteentes en is tussengelaag met die onderste Swakopgesteentes. Piroklastiese vloeie en lawa is aanwesig (fig. 4.6), en die boonste piroklas-tiese afsettings is tussengelaag met die Formasie Chuos en bevat rolsteeninsluitsels [fig. 4.7 (a) en 4.7 (b)].

4.2 PETROGRAFIE

Al die stollingsgesteentes is gedevitrifiseer en bestaan uit fynkorrelrige vergroeiings van kwarts en veldspaat. Devitrifikasie-sferoliete is volop in party monsters (fig. 4.9).

Die geherkristalliseerde arkoosagtige gesteentes bestaan hoofsaaklik uit mikroklien (47-56 persent) en kwarts met ondergeskikte albiet en muskoviet.

4.3 GEOCHEMIE

Die vier Onder-Naauwpoortmonsters wat ontleed is, is tipiese alkaliese rioliete; die monster van die Bo-Naauwpoortlawa onmiddellik onder die Formasie Chuos is bostonities in samestelling.

Die monsters word gekenmerk deur 'n baie hoe K- en hoe Ba-inhoud, 'n hoë K/Rb-verhouding en lae Ca- en Sr-inhoud.

4.4 PETROGENESE

4.4.1 Ontstaan van die opeenvolging

Vulkanisme is met blokverskuiwing langs die ooswesstrekkende Summasverskuiwing wat met die huidige loop van die Löwenfonteinrivier saamval, geassosieer. Die verskuiwing word deur jonger gesteentes verberg. Die stygende magma het die verskuiwingsvlak as toevoerkanaal gebruik. Asvloeie kon nie in 'n noordelike rigting beweeg nie as gevolg van die opgehefde blok en hetin 'n suidelike rigting gevloei. Slegs nadat die afgesakte gedeelte gevul was, kon die vulkaniese gesteentes op die opgehefde gneis afgeset word (fig. 4.10). Vulkanisme het tot 'n einde gekom nadat die eerste Kuisebsedimente afgeset is.

4.4.2 Oorsprong van die magma

Die geochemiese ontledings toon dat die magma kon ontstaan het deur gedeeltelike smelting van granitiese gesteentes wat òf arm aan Rb òf ryk aan biotiet was.

5. GROEP SWAKOP

5.1 STRATIGRAFIE

5.1.1 Algemeen

Die Groep Swakop is onderverdeel in twee hoof-eenhede, die onderste Subgroep Ugab en die boonste Subgroep Khomas. Die Subgroep Ugab bestaan uit drie formasies wat vanaf die basis opwaarts die Formasies Okonguarri, Okotjize en Orusewa behels. Die Subgroep Khomas bestaan uit die Formasie Chuos aan die basis, gevolg deur die Formasie Kuiseb met 'n belangrike karbonaat (Formasie Karibib) naby die basis (kyk fig. 5.1, 5.2 en 5.3).

5.1.2 Litologie

5.1.2.1 *Subgroep Ugab*

5.1.2.1.1 *Formasie Okonguarri*. - Hierdie Formasie bestaan uit skis met ondergeskikte kwartsiet en sanderige kalksteen.

5.1.2.1.2 *Formasie Okotjize*. - Die Formasie bestaan hoofsaaklik uit dolomiet met tussengelaagde skis wat op baie plekke merrelagtig is. In die noorde kom konglomeraat (fig. 5.4 en 5.5) en arkose voor. 'n Basale kwartsiet is op die suidoostelike rand van die Mittenplooi aanwesig. Om die Mittenplooi is die Formasie tussen 200 en 600 m dik en in die Okotjizeplooi meer as 900 m.

5.1.2.1.3 *Formasie Orusewa*. - Die Formasie bestaan hoofsaaklik uit skis en het 'n maksimum dikte van 120 m. Kwartsiet, silikahoudende ysterformasie en dolomietlense is plek-plek tussengelaag.

5.1.2.2 *Subgroep Khomas*

5.1.2.2.1 *Formasie Chuos*. - Die Formasie is oor die algemeen tussen 3 en 10 m dik, maar het 'n maksimum dikte van 200 m in die noorde. Dit bestaan oorwegend uit konglomeratiese skis van glasiomariene oorsprong (fig. 5.3). Die enigste onbe-twisbare tilliet kom op die plaas Löwenfontein 84 voor. Plek-plek is daar dun tussenlae van dolomiet in silikahoudende ysterformasie.

5.1.2.2.2 *Formasie Karibib*. - Die Formasie Karibib het 'n maksimum dikte van 190 m in die Okotjizeplooi, maar word weswaarts dunner totdat dit op die westelike rand van die Mittenplooi heeltemal verdwyn.

Die dikker voorkomste op Löwenfontein 84 en suid daarvan bestaan uit dolomiet gevolg deur kalksteen (fig. 5.6), maar wes van Moedhou 402 is net dolomiet aanwesig. Noord van die Summasberge bestaan die Formasie Karibib uit 10 m kalk-steen aan die basis, gevolg deur 30 m versakkingsbreksie en dan dik, erg gekronkelde, ietwat gebreksieerde dolomiet.

5.1.2.2.3 *Formasie Kuiseb*. - Die Formasie Kuiseb wat tot meer as 9 800 m dik is, bestaan hoofsaaklik uit goedgefolieerde mikaskis, met ondergeskikte tussenlae van kwartsiet en dolomiet. Die oorspronklike opeenvolging het uit gelyke hoeveelhede grouwak, subgrouwak en skalie bestaan.

5.2 FASIESVERANDERINGE

Die enigste chronostratigrafiese eenheid in die hele opeenvolging is die Formasie Chuos, en dus kan eenhedeonmiddellik bo en onder die Formasie in 'n mate chronostratigrafies gekorreleer word.

Die duidelikste fasiesverandering in die Formasie Okotjize is die oorgang van gelaagde en massiewe dolomiet in die ooste na dungclaagde dolomiet op Groenpoort 403. Tussengelaagde silikahoudende ysterformasie met 'n dikte van 55 m in die Formasie Okotjize en Orusewa op Groenpocit 403 verdwyn heeltemal in 'n westelike rigting binne 'n strekkingsafstand van 200 m. Net wes van hierdie lokaliteit word die dolomiet aansienlik dikker en verteenwoordig heel waarskynlik 'n afsluitrif (fig. 5.7).

Studies van insluitsels in die Formasie Chuos toon dat dele van die Formasie van dieselfde ouderdom kan wees as die boonste skis in die Formasie Orusewa.

5.3 OORGANG TUSSEN DIE GROEPE SWAKOP EN OTAVI

Die onderste gedeelte van die Groep Swakop is baie soortgelyk aan byna die hele Groep Otavi; daar is litologiese deurlopendheid tussen die twee en die tussengelaagdheid van die Formasie Chuos toon 'n noue tydekwivalensie. Karbonate is in vlakwater afgeset. Na afsetting van die Formasie Karibib het die gebied suid van die Kamanjabvenster vinniger gedaal, baie meer detritus is ingespoel en die Kuisebsedimente is afgeset. Noord van die venster het vlakwatertoestande geheers en karbonaat is verder afgeset. Dit is dus op hierdie stadium dat die hoofverskille in die litologie van die twee groepe ontwikkel het. Die daling in die suide het vanaf die rand van die Kamanjabvenster plaasgevind en die skrywer is van mening dat al die sedimentere gesteentes suid van die Fransfonteinrug uitsluitende die van die Groep Mulden by die Groep Swakop ingesluit behoort te word.

5.4 OUDERDOM

Stromatoliete in die onderste gedeelte van die Groep Otavi het waarskynlik 'n ouderdom van tussen 600 en 1200 Ma (Cloud en Semikhatov 1969); sirkoon van Naauwpoortporfiere het 'n ouderdom van 720 en 750 Ma gegee (Burger en Miller, in voorb.).

5.5 STRUKTUUR

Die vroegste tektoniese gebeurtenisse het gelyktydig met afsetting plaasgevind. Plaaslike opheffings het diskonformiteite aan die basis van die Subgroep Ugab en Formasie Chuos veroorsaak. 'n Derde opheffing het tot versakkingsbreksies in die half-gekonsolideerde Formasie Karibib gelei.

Na afsetting het groot oos-wesstrekkende plooie (F_1) ontwikkel met golflengtes van 'n paar kilometer. Latere, baie sterker vervorming het tot nou, noordoos- en noordwesstrekkende plooie (F_2) en 'n goedontwikkelde kliewing gelei (fig. 8.1). F_1 en F_2 is ouer as die Salemgraniet.

Die enigste Fs-struktuur is ‘n kliewing in die noordweste met oosnoordooswaartse strekking. Dit is jonger as die Salemgraniet. F_4-strukture is beperk tot plaaslike kinkelplooie in die F_2-kliewing (fig. 8.15 en 8.16).

6. NA-DAMARAMETAMORFOSE

Die piek van regionale metamorfose was na-tektonies en het geeindig in smelting en die vorming van die Suite Salem en Sorris-Sorris-Graniet. Intrusie van die Salemgraniet het ‘n opvallende termale oureool gevorm.

6.1 METAMORFOSE VAN FORMASIE NAAUW POORT

Gedurende metamorfose het die Naauwpoortgesteentes gedevitrifiseer geraak, geherkristalliseer en uiteindelik hersmelt. In die noorde is die vulkaniese gesteentes gedevitrifiseer, maar behou nog hul vulkaniese voorkoms. Suidwaarts neem die korrel-grootte toe en die gesteentes word arkoosagtig (fig. 4.8). Konkordante sekresiepegmatiete is die produkte van die begin van smelting (fig. 9.2). Verdere smelting het die Sorris-Sorris-Graniet gevorm.

6.2 METAMORFOSE VAN GROEP SWAKOP

6.2.1 Karbonaatgesteentes

Die korrelgrootte van die karbonaatgesteentes neem suidwaarts toe. In dieselfde rigting verskyn chloriet, talk, tremoliet, diopsied, forsteriet, skapoliet, fiogopiet, plagioklaas en monticelliet in die genoemde volgorde (fig. 9.4 en 9. 5).

6.2.2 Pelitiese gesteentes

Chloriet-muskovietskis met baie ondergeskikte biotiet is die volopste.

Namate die kontak met die Salemgraniet genader word, verskyn biotiet, cordieriet, kaliveldspaat en plaaslik sillimaniet en almandien in volgorde.

6.2.3 Druk-temperatuurtoestande van die Damarametamorfose

6.2.3.1 *Regionale metamorfose*

Gedeeltelike smelting van die Kuisebskis en diopsiedreaksies dui op ‘n druk van tot 5 kb en ‘n temperatuur van meer as 655°C.

6.2.3.2 *Termale metamorfose*

Die vorming van sillimaniet uit muskoviet en cordieriet uit klinochloor dui op ‘n druk van 3,5 kb op die suidelike rand van die Mittenplooi, en die vorming van diopsied 1 km vanaf die Salemgraniet dui op ‘n temperatuur aldaar van omtrent 610 °C.

7. GROEP MULDEN

Die gesteentes bestaan uit gefolieerde chlorietskis met baie ondergeskikte kalksteenlense. Plooiasse strek ooswes.

7.1 MINIMUM OUDERDOM VAN GROEP MULDEN

Die Muldengesteentes is gedurende die F_2-vervor ming wat na-Damara in ouderdom is, geplooi. Die Rb/Sr-ouderdom van die na-tektoniese Salemgraniet is 540 Ma. Die Mulden is dus ouer as 540 Ma.

8. ONTWIKKELING VAN DIE NOSIB-SWAKOP. EN MULDENBEKKEN IN DIE HUIDIGE GEBIED

Die bekkens het soos volg ontwikkel:

Opheffing en erosie in die noorde, afsetting van konglomeraat op die suidelike rand van die Kamanjabvenster, en afsetting van sandsteen en grouwak verder suid.

Grootskaalse blokverskuiwing, plaaslike vulkanisme en grabenagtige sakking in die suide. ‘n Dik opeenvolging het in die nuutgevormde tektoniese trog gevorm.

Plaaslike kleinskaalse opheffing en erosie, gevolg deur algemene maar ongelyke sakking en mariene oorskryding. Vlakwatertoestande en afsetting van karbonate. Vulkanisme het met hierdie fase van afsetting saamgeval.

Plaaslike opheffing en wydverspreide vergletsering met vier ondergeskikte glasiale terugwykings. Vulkanisme het gedurende hierdie vergletsering tot ‘n einde gekom.

Afsetting van baie pelitiese sedimente en ‘n bietjie karbonaat.

Vervorming het gedurende hierdie afsettingsperiode begin of net na die beeindiging daarvan.

Dit het plek-plek tot opheffing en erosie aanleiding gegee. Gedurende die vormingsfase is Mulden sedimente in intermontane gebiede afgeset. Hierdie lae is gedurende die finale fase van vervorming geplooi.

9. NA-DAMARAGRANIET

9.1 SUITE SALEM

Horingblende-biotietdioriet wat ‘n randsone van 1 km breed by Otjozondjou vorm, gaan oor in monsodioriet gevolg deur die hoofiiggaam van Salemgraniet, biotietmonzoniet en graniet. Laasgenoemde is kalsiumryk naby Otjozondjou waar dit ook baie ondergeskikte horingblende bevat, maar na dit word meer kaliumryk na die weste toe. ‘n Paar dun pegmatiete kom voor op Sorris-Sorris 186. Die verspreiding, petrografie, geochemie en petrogenese van die suksessie is reeds in detail deur Miller (1974) beskryf.

9.2 SORRIS-SORRIS-GRANIET

Die Sorris-Sorris-Graniet wat deur smelting van die Naauwpoortgesteentes ontstaan het, is middelkorrelrig, rooi, ligroos of grys, en intrudeer hoofsaaklik die Salemgraniet (fig. 10. 1 en 10.2). Daar is egter ook klein indringings in die Naauwpoort- en Kuisebgesteentes. Daar is geen geochemiese verskil tussen rooi en ligroos soorte nie.

Al die monsters wat ontleed is, is alkalies. Hulle bevat meer Ca en Sr en minder Ba as die Naauwpoortgesteentes en is ook nie so kaliumryk nie. Lae K/Rb, en Ba/Rb-verhoudings dui op ‘n geringe mate van differensiasie.

10. OPEENVOLGING KAROO

Die Opeenvolging Karoo in die huidige gebied bestaan uit sedimentere gesteentes van die Formasies Dwyka, Prince Albert en Omingonde en jonger veldspaatporfier.

10.1 FORMASIES DWYKA EN PRINCE ALBERT

Die Formasie Dwyka kom tussen Otjomkona en Okongwe voor en bestaan uit tilliet. Die voorkoms van die Formasie Prince Albert is te klein om op die kaart aangedui te word. Die afsetting kom op die oostelike rand van die Okotjizeplooi voor en bestaan uit grys skalie met 'n paar dun kalksteenlae en verskeie groot karbonaatkonkresies.

10.2 FORMASIE OMINGONDE

Die Omingondegesteentes bestaan uit rooi, ligroos en wit moddersteen, grintsteen en konglomeraat en is tot 230 m dik.

10.3 VELDSPAATPORFIERPLATE

Die meeste van die plate is horisontaal maar 'n paar in die noorde het hellings van 45°. Voergange is vollop in die Kuisebskis net noord van die Otjongunduplato. Tot agt plate is gevind. Die plate is effens blasiesrig. Eerstelinge bestaan hoofsaaklik uit kaliveldspaat en plagioklaas, maar 'n paar kwartseerstelinge is in twee plate gevind. Die grondmassa is baie fynkorrelrig maar grafiese vergroeiings is ook herkenbaar. Ontledings toon dat die plate die samestelling van alkaliese rioliet het. Die voergang wat ontleed is, kan bestempel word as ooralkaliese tragiet.

10.4 DOLERIET

Doleriet van Karoo-ouderdom kom as gange en redelike dik plate in al die ouer gesteentes voor. Mineralogies het die gesteentes die samestelling van doleriet of oliviendoleriet met tussenkorrelse tot subofitiese tekstuur. 'n Paar gange is eukrities in samestelling. Baie van die plate en breë gange het 'n gevlekte voorkoms as gevolg van ougieteerstellinge (tot 8 mm in deursnee) en het 'n ofitiese tekstuur.

11. INTRUSIEWE GESTEENTES JONGER AS DIE OPEENVOLGING KAROO

11.1 KOMPLEKS OKENYENY A

Die kompleks word deur Simpson (1954) beskryf.

11.2 OTJOHORONGO-GRANIET

Die Otjohorongo-Graniet vorm 'n gesoneerde koepeltjie van alkaliese graniet en granietporfier met geassosieerde kring-, tregter- en lineere gange van kwartsporfier en apliet.

11.2.1 Granietkoepeltjie

Die koepeltjie is kringvormig en bestaan uit 'n buitesone van geel grofkorrelrige graniet en 'n binnesone van granietporfier. Die binnesone gaan oor in middelkorrelrige graniet met min eerstelinge naby die middel van die liggaam.

Die buitesone met 'n maksimumbreedte van 1,5 km toon geen verkilling op die kontak met die skis nie. Die sone is baie onderbroke en word op talle plekke gei'ntrudeer deur die jonger granietporfier wat gewoonlik gangvormig is. Die "gange" is van 'n paar tot 250 m breed en in 'n oossuidoostelike rigting georienteer. Baie daarvan sny dwarsdeur die graniet tot in die skis waar dit ook geen kilsones toon nie.

Die middelkorrelrige sentrale gedeelte is net omtrent 500 m in deursnee en 'n gang van hierdie gesteente sny die twee buitesones. Die gange word deur enkeles van apliet gesny.

Die gesteentes het die mineralogiese sames telling van graniet of adamelliet. Kaliveldspaat is pertities en plagioklaas varieer van An_o tot An_6 in samestelling.

11.2.2 Kringgange

Altesaam 17 gange is gevind. Die meeste is van kwartsveldspaatporfier, maar daar is ook vyf aplietgange. Van laasgenoemde is daar twee soorte, een met mikroklien en die ander met onvertweelingde kaliveldspaat. Dun breksiesones kom voor in 'n paar gange en word deur chert, fluoriet of skorl gesementeer.

11.2.3 Tregter- en lineere gange

Hierdie gange is mineralogies baie soortgelyk aan die kringgange van porfier.

11.2.4 Geochemie

Die graniet-, kring- en tregtergange is almal alkalies in samestelling. K/Rb-verhoudings vir al die gesteentes is laag en dui op differensiasie. Die graniet (K/Rb=77) is baie meer gedifferensieer as die tregtergange (K/Rb= 185).

Die opeenvolging van gebeurtenisse was waarskynlik soos volg:

(1) Eksplosiewe aktiwiteit, vorming van tregter-breuke en intrusie van riolitiese magma met 25 per sent vaste stowwe.

(2) Verskeie periodes van eksplosiewe aktiwiteit, vorming van kringbreuke en intrusie van magma. Pouses tussen indringing was lank genoeg om die magma betekenisvolle differensiasie te laat ondergaan.

(3) Indringing van die grofkorrelrige graniet; min vloeistowwe.

(4) Indringing van die granietporfier en vorming van uitsettingsnate wat deur granietporfier gevul word. Die mikroklienbevattende gange bevat baie skorl wat op intrusie op 'n baie laat stadium dui.

11.3 KWAGGASPAN-KARBONATIET

Die liggaam bestaan uit vyf klein proppe in 'n ry, twee van karbonatiet, een van kwarts-hematiet¬muskoviet en twee van fynkorrelrige ysteroksied en silika. Die proppe het in 'n breksiesone in die Kuisebskis wat deur gange van sövitiese karbonatiet gesny word, ingedring.

Die westelike prop met 'n deursnee van 150 m is die grootste en bestaan hoofsaaklik uit sövitiese karbonatiet met baie gedissemineerde hematiet. In die middel van die prop is daar groot xenoliete van gestreepte ysterklip, dolomiet en skis wat almal in 'n mindere of meerdere mate gebreksieer is. Naby die noordwestelike rand van die prop is 'n liggaam van hoegraadse hematieterts met 'n deursnee van 10 m.

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