THE REGIONAL TECTONISM

OF THE GNEISSES

OF PART OF NAMAQUALAND

by

P. JOUBERT

The University of Cape Town

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ABSTRACT

A reconnaissance survey of the gneisses of an area some 12,000 km^2 in extent was conducted in order to determine the geology of the country between the existing geological maps of Bitterfontein in the south and the Richtersveld in the north. The basal rocks are augen gneisses overlain by pink gneisses in the east, succeeded in ascending order by leptites, aluminous rocks, quartzites and mafic gneisses. The paragneisses accumulated before ±2,600 My ago and have been folded and sheared during three events of deformation, each consisting of several episodes with accompanying metamorphism.

The earliest recognisable deformation which resulted in the tectonic banding was followed, prior to ±1850 My ago, by isoclinal folding and the associated metamorphism is recorded by zones of distinctive mineral assemblages ranging from greenschist facies at the coast to granulite facies in the east. Subsequent east-west folds, commonly monoclinal in style, with concomitant shearing and tectonic sliding, are responsible for the present prevalent direction of strike of the banding and at the same time large interference structures developed. The first event culminated in the emplacement of granites and pegmatites when open folds formed. The pegmatites occur along an east-west belt to the north of the present area, separating the Namaqualand gneisses from the less-recrystallised rocks farther north. This thermal event, thought to be responsible for the generation of much cordierite as well as wollastonite, probably resulted in the prevalent ±1000 My age returned by the rocks in Namaqualand.

During the second event shearing took place under amphibolite-facies metamorphic conditions and the basal part of the Stinkfontein Formation was deposited, probably ±900 My ago, along a north-south trough near the present coast. Large phyllonite zones developed during deformation of the third event when the Upper Stinkfontein Formation accumulated in basins oblique to the strike of the basal sediments and where vertical tectonics in the floor caused gravitational gliding of the sediments. Numerous mafic dykes (±870 My), supplying the volcanic material interbedded with the sediments, were intruded in the coastal regions. The Richtersveld granites (±850 My) were emplaced and the thermal effects recorded by the generation of new minerals. The Nama

sediments (±600 My) were deposited and followed by rejuvenation of movement along existing north-south lines of structural weakness.

East-west fractures with dolerites (190-150 My) emplaced along them, developed and were followed by strong north-south fracturing resulting in the complicated horst-like structure of the Kamiesberg.

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I. INTRODUCTION

A. GENERAL

The area under discussion is situated in the north-western part of the Cape Province known as Namaqualand and includes two north-south rectangular areas joined by an east-west strip. The area in the north-west is bounded by longitudes 17°00' and 17°30'E and latitudes 29°00' and 29°45'S and is situated to the east of the small port of Port Nolloth on the west coast of South Africa and to the west of the village of Steinkopf. The area to the south-east covers the region between the towns of Springbok and Bitterfontein and lies to the east of the villages of Garies and Kamieskroon. It is bounded by longitudes 18°00' and 18°30'E and latitudes 29°45' and 31°00'S and is joined to the area in the west by a strip between latitudes 29°45' and 30°00'S to the south-west by Springbok.

The mapping was carried out during the period March, 1967 to August, 1969 and an area of approximately 12,000 km^2 was covered. The work was carried out for the Chamber of Mines Precambrian Research Unit attached to the Department of Geology of the University of Cape Town and was financed by a grant from the Anglo American Corporation of South Africa, Limited.

The population is mainly centred on the copper-mining district in and around the towns of Springbok, O'okiep and Nababeep. Elsewhere the area is sparsely populated by the farming community and because of the arid conditions, the farms are large and most of the sheep farmers have other grazing in Bushmanland when Namaqualand is very dry. In years of good rains, the area yields satisfactory crops of wheat and Namaqualand is well known for its flowers carpeting most of the area after good winter rains.

Large areas in Namaqualand have been set aside for the people of coloured extraction and parts of their lands were covered by the present survey. These include parts of the Coloured Reserves of Rietpoort in the south, Leliefontein, centrally situated in the eastern region mapped, Komaggas on the western side of the east-west strip and the Reserves of the Richtersveld, Vioolsdrif South and Steinkopf in the north. These people tend to cluster in small communities where the country is almost denuded of vegetation, while leaving large tracts of their land unpopulated.

Bitterfontein, just south of the southern boundary of the area, is the railhead and since the survey the tarmac road from Bitterfontein through Springbok to Vioolsdrif has been completed. The secondary earth roads are usually kept in good repair and there are numerous small tracks on most of the farms.

As in other arid parts in the world, water is of prime importance and boreholes yielding strong supplies, usually of brackish water, are mostly sited on the many north-south faults traversing the area, but sometimes the metaquartzites are the aquifers. On the coastal flats west of the escarpment where faults are difficult to locate because of the sand cover, good boreholes are rare. Water for the mining community is derived from the alluvium in the Buffels River at Drie Rivier, north-east of Komaggas.

B. MAPS

The maps were drawn on a scale of 1:50,000 and reduced to 100,000 for printing. Much of the geological details was taken from aerial photographs otherwise this large area could not have been covered in the allotted time; the mapping was therefore effected in reconnaissance style and the maps should be viewed as such. Geological detail was transferred from aerial photographs onto the maps by means of a camera lucida, a method which is quick, but not always very accurate. For the eastern part of the area topographic base maps on a scale of 1:50,000 were used; some of these only became available after the survey and the geology had to be transferred onto them afterwards. For the rest of the area topocadastral sheets with farm boundaries and trigonometrical beacons providing the ground control, were used. As the topographical variations on the coastal flats are not very great, little difficulty was experienced in compiling the maps there, but the compilation of the strip joining the two north-south parts proved to be troublesome and involved, especially towards the west where there is much variation in altitude over short horizontal distances and in places a plane-table had to be used. Therefore, the map of the eastern block is the most accurate, while the western block is less so and in the central part joining the eastern and western sections, the accuracy in some regions is rather uncertain.

Airphoto mosaics for part of the western area were available and these were reproduced by copyright release No. 4081 of 20th November, 1968 of the Government Printer, but could not be used as the scale was inaccurate.

C. PREVIOUS GEOLOGICAL WORK

Of all the reports mentioned below, only those of Rogers (1912), Brink (1950) and Pike (1959) described the geology of parts of the present area, while Gevers (1940) noted some of the geology seen by him during a mapping program. Some mineral occurrences of the area are described in conjunction with similar deposits elsewhere.

It is only to be expected that the first geological reports on Namaqualand should be in connection with the copper deposits occurring north of the present area. Wyley (1857) travelled over a wide area and described the geology of 61 mines and copper occurrences between the O'okiep area and the Orange River. He remarked on the fact that most of the socalled schists are of a gneissose character and distinguished between the type of copper occurrences in the south where the ore-bodies are large and irregular in shape and those of the north which are found in narrow strips along the foliation of the schists or in association with quartz veins.

On his map of the O'okiep area, Kuntz (1904) showed five parallel lines striking east-northeast along which the ore-bodies have been intruded as well as west-northwest "lines of breaks" and was of the opinion that copper mineralisation is concentrated at the junctions of these two fracture directions. In his description of the country and its geological features Ronaldson (1905) also noted that copper-bearing "veins" occur along five well-defined belts shown on his map as being due east-west, but their positions do not always coincide with those of Kuntz.

In his Presidential Address to the Geological Society of South Africa, Rogers (1916) described the nature of the copper deposits of Namaqualand, while Latsky (1942) extended the scope of this line of investigation. Latsky also observed that Tolmann and Rodgers (1916) established the magmatic origin of the Namaqualand ores and that Delesse (1855) described the occurrence of tetrahedrite at Spektakel, a mineral which does not appear elsewhere and has not been found since. Read (1952) suggested that the basic bodies represent resisters which have been derived from original basic flows and have been dismembered during granitisation.

More recently a most comprehensive report on the geology and ore-bodies of the mining district has been compiled by the geologists of the O'okiep Copper Company, who have successfully exploited the area since 1938 (Benedict, et al., 1964). Since then a report on the geology of one of the mines has appeared in print (Van Zyl, 1967) and a recent geochemical and mineralogical investigation in the variations in the wallrocks of the ore-bodies indicated the igneous origin of these rocks (Prins, 1970).

Systematic regional geological mapping was initiated when Rogers and Schwarz (1900) surveyed an area to the south of the present area and found granite and gneiss in the north-eastern part of the Vanrhynsdorp district. They described these rocks as extending from there to the Orange River and also correlated them with similar rocks found in parts of Bushmanland. They gave descriptions of the more common types of gneisses and granites encountered as well as some structural details. This work was carried further by Rogers (1904) when the pyroxene granulites and sillimanite-cordierite gneisses were discovered. Rogers (1912) then extended the survey as far north as Steinkopf and reported at length on the geology of the area where copper was being mined. He mentioned (op. cit., p.149-150) the presence of quartz schists, felspathic quartzites and conglomerates along the coast and proposed the name "Port Nolloth Beds" for them. Later (Rogers, 1915), after mapping the rocks of the Richtersveld, he relinquished this name in favour of the Stinkfontein Series which he included with what he termed the "Western Folded Nama". He also described the staurolite schists, now considered to belong to rocks of Kheis age, as being interbedded with the Stinkfontein quartzites and as a result found granites of post-Nama age.

Strauss (1941) in his valuable contribution to the understanding of the general geology of the Namaqualand gneisses, first established part of the geological sequence of the paragneisses and the major structural features in the O'okiep area.

Brink (1950) examined a large area east of Bitterfontein including the south-easterly region of the present map and reported on the gneisses and overlying Nama sediments. The regions around Bitterfontein and adjoining the present area to the south were mapped by Jansen (1960) who regarded the gneisses and metasediments as the metamorphosed representatives of the Malmesbury Formation, a view which Pike (1959), mapping farther to the east, accepted. Pike determined a sequence in the gneisses there and this was confirmed during the present survey. Kröner (1968) reinvestigated part of the area mapped by Jansen and proved that the gneisses are unconformably overlain by the sediments.

To the north of the area described in this report, part of the Richtersveld was examined by van Biljon (1939) followed by a comprehensive study of the varied geology of the whole of the area (Söhnge and de Villiers, 1946; De Villiers and Söhnge, 1959). Middlemost (1964, 1965, 1966) gave further details on the Stinkfontein Formation and on some of the intrusive rocks. To the east of the Richtersveld the regions, where the geology is similar to that of the present area, along the Orange River as far as Upington, have been reported upon and mapped (Coetzee, 1941, 1942; Poldervaart and von Backström, 1949; von Backström, 1964, 1967; von Backström and de Villiers, in the press).

The granites of Namaqualand received special attention from Mathias (1940), Gevers (1940), Coetzee (1941), Nel (1950) and von Backström (1964), while the geology of the pegmatite belt north of the present area was described by Gevers (1936) and Gevers et. al. (1937). The easterly continuation of this belt of pegmatites was the subject of Hugo's (1965) thesis and Taljaard (1937) included descriptions of the occurrences of melilite basalt of the present area in his discussion of these rock types.

A number of mineral occurrences in Namaqualand and Bushmanland have been described and those having a bearing on the geology of the present area have been reported by Mathias (1940a), Coetzee (1941a, 1958), Söhnge (1950), von Backström (1950), Pike (1959), and De Jager and von Backström (1961). De Jager (1963) described various sillimanite occurrences of Namaqualand, one of which occurs in the present area, while De Jager and Simpson (1962) gave an account of the wollastonite occurrences near Garies.

Apart from the accounts of the geomorphology of the various areas reported on and mentioned above, this aspect of Namaqualand was investigated by Mabbutt (1955) who distinguished two main erosion surfaces in contradiction to Rogers (1911) and Reuning (1931) who considered the tops of the Kamiesberg as the westerly continuation of the Bushmanland Plateau. Du Toit (1933) considered the Kamiesberg as lying on the westerly extension of his Griqualand-Transvaal axis of crustal warping.

Martin (1965, p.59-71) reviewed the geology of Namaqualand and discussed the relationship to the Kheis System, the age of the gneisses, the copper deposits and the pegmatite belt. Later he (Martin, 1969, p.19-21) amplified his views on the dating, structure and metamorphism of the gneisses. Nicolaysen (1962) advocated a new approach to the stratigraphic position of the Kheis System in view of the isotopic dating and later Nicolaysen and Burger (1965) considered the possibilities in explaining the contradictory 1,000 My age and recorded the age measurements of rocks within and around the present area.

D. PURPOSE OF THE SURVEY

Apart from the excellent and detailed, mostly unpublished geological maps of the copper-mining district around O'okiep, the geology of Namaqualand, between latitudes 31°00'S in the south and 29°00'S in the north has not been mapped or systematically examined. Geological Survey maps are available to the south (Jansen, 1960; von Backström, 1960) and to the north (De Villiers and Söhnge, 1959) of the present area; except in connection with the occurrence of copper and the geology relating to that area, the knowledge of the geology was confined to a few scattered localities where minerals of economic importance occur.

The main purpose of the present survey was to map as much as possible in the allotted time of the area between those of the existing Geological Survey maps and to obtain information on the geological succession and the tectonic and metamorphic history of the gneissose rocks.

It is intended that this work should stimulate interest and be followed up by detailed tectonic and metamorphic studies.

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The thin sections for the investigation were prepared by the Geological Departments of Anglo American Corporation of South Africa, Limited, O'okiep Copper Company and the University of Cape Town. The geologists at O'okiep, especially Messrs. A.F. Lombaard, B. de V. Packham, S.G. Hausmann and F.J.G. Schreuder rendered assistance in kindly showing and explaining the geology around O'okiep. Mr. H. Jenner-Clarke of Springbok assisted in locating most of the numerous kimberlite occurrences.

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II. PHYSIOGRAPHY AND DRAINAGE

King (1963) divided the area into two regions; the highlands were correlated with the Cape Middle Veld and the coastal plains with the Namib, both of which he assigned to the post-"African" cycle of denudation. Morphologically the area can be divided into four regions: 1) The coastal plains, 2) an intermediate surface, 3) the highlands and 4) the Bushmanland Plateau.

The coastal regions are flat sand-covered plains in the south, rising fairly quickly from sea-level to an elevation of approximately 200 m and then gently sloping up towards the east to the foot of the escarpment which generally lies at about 350 m above sea-level. Towards the north residual hills become more numerous and the hill ranges comprised of the Stinkfontein quartzites and its basement become continuous.

The Buffels River, which flows only for short periods after heavy rains, crosses the area from east to west and is joined by the other major drainage channels, the Stryd, Mara and Komaggas Rivers, draining the escarpment.

In the north an interesting situation exists as all the rivers from the north-east and east drain into a wide sand-covered plain between the farms of Oograbies and Breekhoorn and dry pans are found in a number of places. Towards the east the plain bifurcates; one side continues to the north-east past Soetwater while the other continues to the east, south of the outcrops at Nanassen towards Knie Brand. The gap in the Stinkfontein hills at Gemsbokvlei is the only exit from this basin to the sea and surface water only rarely utilises this gateway in the event of local downpours. The local farmers maintain that water flows subteraneously from Soetwater in the north-east, past Nieuwe Fontein and through the gap in the hills at Gemsbokvlei as proved by the good boreholes in a number of places along this line.

The Kamma River drains the Lekkersing area and the line of Stinkfontein hills there. It has cut a fairly deep channel on the north-western side of the area, but soon after turning to the west onto the sandy plains, the channel disappears.

The intermediate surface occupies the high ground east of the coastal flats on the east-west strip of the map and slopes up from an elevation of more than 500 m on the Kourkamma Hills in the west to over 700 m in the east where it can be seen to be an exhumed fossil surface from which the Nama sediments have mostly been stripped. Remnants of sediments of Nama age form the flat-topped plateaux in the northern part of this area and continue farther north to the west of Springbok. The channel of the Buffels River crosses this area from east to west up to south-west of Koornhuis from where it turns to the north-northwest and follows a strongly developed zone of fracturing where the channel can be seen changing direction when crossing from one fracture zone to another.

It is of interest to note that the largest part of this surface lies at an elevation which Mabbutt(1955) records as the elevation of a subcycle of denudation.

The highlands include the high ground and mountains of the Kamiesberg east of the intermediate surface and lie along a north-northwest belt across the country and appear to have been controlled by faulting prevalent in the same direction and along the same zone. The highest peaks of the Kamiesberg lie almost on the water divide stretching from south of Platbakkies towards the west to north of Eselskop trigonometrical beacon from where it swings north-west coinciding with a faulted zone on the western boundary of the present area. The water divide probably coincides with the Griqualand-Transvaal axis of crustal warping (Du Toit, 1933), but contrary to the description of the axis farther to the east, the southern slope is considerably greater than that of the north. The northern slope of the Kamiesberg forms part of the catchment area of the Buffels River. The channel of this river commences along a fault to the east of Leliefontein trigonometrical beacon and after following the fault for some distrance in a north-northwesterly direction, swings to the east up to Paapkuils Fontein from where it follows another north-northwesterly fracture. From Tweefontein the channel of the Buffels River continues to the west, generally parallel to the strike of the gneisses.

The highest peak, Roodeberg (Welkom trigonometrical beacon) reaches higher than 1,800 m above sea-level, while some distance to the north, Eselskop is approximately 1,700 m in elevation. Farther north the beacon hills of Leliefontein and Anegas reach up to approximately 1,500 m.

To the south of the divide, the surface of the area slopes rather rapidly so that an elevation of 300 m is reached at places along the southern boundary of the area. The geological maps clearly show the deep valleys incised into the southern Kamiesberg along the north-south faults. In the east the channel of the Hartbees River at first proceeds south and at Draaihoek turns to the west to join the Swartdoring River at Groot Riet. This latter river also commences in a north-south course, but at Groot Riet, turns into the hills where it follows a deeply incised young valley because of river capture there, and it only attains a more mature valley to the west of the main road between Bitterfontein and Springbok. Along the western boundary of the area the Dikdoring River enters the area south of Garies and again leaves the area farther south to join the Swartdoring River to the west. Most of the area in the south-west is the catchment for the Swartdoring River, but the area in the south-east is drained from the south.

Much of the surrounding area of the highground and to the east along the divide lies at 1300-1400 m (4,000 ft.) above sea-level and therefore coincides with the elevation of the Namaqua Highland surface of Mabbutt (1955) which he correlated with Kaap Plateau (Du Toit, 1908-1910) and dated as Cretaceous. It does appear that a bevel older than the Bushmanland Plateau exists in the area of the mountains and the evidence supports Mabbutt's suggestion that this area is not just the western projection of the Bushmanland Plateau as recorded by Rogers (1911), Reuning (1931) and King (1963, p.238).

The Bushmanland Plateau dated as early-Middle Tertiary by Mabbutt (1955) covers the north-eastern corner of the present area in the east and its western edge lies along a line from Platjes Fontein in the north to Platbakkies in the south from where the plain stretches out to the east. Its elevation coincides with the elevation of 1000-1100 m recorded by Mabbutt for this bevel.

In the vicinity of Platbakkies kaolinised gneisses and clayey grits occur along north-south faults and mark the position of old drainage channels. These deposits straddle the axis of the crustal warping, according to Mabbutt, of mid-Tertiary and later date and are therefore older than the warping. Patches of kaolin in places in the hills to the west may perhaps mark the position of the westerly slope of this surface.

Since the development of the Bushmanland Plateau deep valleys encroached on the high ground from the west and these were later filled in with thick deposits of red sand smoothing the area to the west of the plateau. During this stable phase wide mature valleys between the hills formed, like that from north of Dabeeb to Rietfontein. Subsequent re-excavation of the valleys, taking place even at present time, has cut deep gorges into the sand especially in the area between Kaauwgoed Vlakte and Matjeskloof.

III. SUMMARY OF THE PRECAMBRIAN GEOLOGICAL HISTORY OF THE AREA

In the descriptions of polyphase deformation and metamorphism there is no consistency in the terms employed for the successive events affecting the rocks and recently Krasil'nikov (1969, p.428) has suggested that an "orogenic stage" be divided into "phases" and "subphases" of deformation. However, here the terms "event" consisting of "episodes" of deformation and metamorphism as proposed by Sutton (1965), will be used.

The complexity of the geology of the gneisses of Namaqualand is obvious since three events, each consisting of several episodes during which the rocks have been deformed, can be distinguished. With only very few age determinations at hand, the sequence of events as given in Table 1 must of necessity be rather tentative in part.

Event	Episode	Deformation	Intrusives
		E-W faulting; minor crenulations locally	Dolerites of
			Kuboos Granite
		N-S and NNW faulting and minor folding; rejuvenation of movement along existing lines of weakness. Step-faulting east and west of Kamiesberg	
		Deposition of sediments of Nama age	
III	F_9	N-S shearing and minor folding and fracturing	Richtersveld Granite
		Deposition of Upper Stinkfontein Formation and gravity tectonics	
	F_8	NNE shearing and shear folds with minor conjugate folding and kink-banding. Folds plunge north	
		Deposition of Lower Stinkfontein Formation	
II	F_7	N-S shearing with minor folds plunging north; formation of trough along west coast	Pegmatites
	F_6	NE shearing and concomitant folding; open gently plunging to tight steeply plunging NE	Small pegmatit basic dykes an ment of basic
	F_5	WNW shearing and associated folding; open gently plunging to tight steeply plunging west	Small pegmatit
I	F_4	Open folding, occasionally conjugate; associated NW fractures and mylonites. Mild cross-folding	Concordia-type Emplacement of tites along be
	F_3	Variable fold styles; tectonic sliding and shearing along EW zones with s_3 and l_3 strongly developed. Periclinal interference structures	Incipient gene Concordia-type Emplacement of mafic intrusiv
			? Vioolsdrif G
	F_2	Isoclinal folds, now at various attitudes from recumbent to upright. Strong recrystallisation; s_2 originally NNW trend; l_2 mineral lineation, rodding, mullion, etc., originally moderate to gentle plunge northwards	Basic intrusiv sheets emplace
	F_1	Tight intrafolial folds; s_1 tectonic banding and ?biotite foliation	Granites NW of Streaky gneiss Bitterfontein?

TABLE 1. EPISODES OF

GNE

tentatively correlated with the Kheis rocks, mainly because of the presence of quartzites and mafic rocks. It is clear that a complete sequence as defined by Rogers is not represented in Namaqualand. In the early reports on the areas underlain by Kheis rocks the base of this group has never been described, but Rogers and du Toit (1908, p.19) recorded the presence of arkose with some grits and phyllites followed by cleaved igneous rocks which they regarded as possibly representing the lowest portion of the Marydale group to the west of Prieska, but judging by the description, it is possible that this part of the sequence is in fact the basal part of the Kaaien quartzite which again appears on the western side of the Doornberg fault there (personal observation).

Rogers and du Toit (1908, p.18) noted that the great mass of sediments and detrital rocks consisting largely of granite debris indicate that, although never seen, the base on which the Kheis rocks lie must have been made up of granite at least in part.

From the regional mapping over a wide stretch of country during the present survey, it has become apparent that, if the quartzites found in Namaqualand are to be correlated with those of the Kaaien, then the entire thickness of the underlying Marydale volcanics between the present area and the Richtersveld and Prieska is missing. On the other hand, it is also possible that the Kaaien quartzites are not represented in the present area and that the quartzites there occur at or near the base of the Kheis succession.

The Kaaien quartzites from west of Prieska (Rogers and du Toit, 1908) to Upington-Keimoes (von Backström, 1964) and farther east (van Backström and de Villiers, in the press) to the Richtersveld (De Villiers and Söhnge, 1959) overlie a thick succession of Marydale lavas; there is frequent mention of sedimentary structures, they are often conglomeratic at the base and they attain great thicknesses whereas the quartzites in the present area are completely recrystallised, sedimentary structures and conglomerates were never seen and great thicknesses are only attained by repeated tight folding. None of these facts militates strongly against\ correlation of the Namaqualand quartzites with the Kaaien quartzites, but these features, together with those mentioned below possibly indicate that the quartzites in the present area represent the basal part of the Kheis group of rocks.

When the mapping of the present area started, the great variety of types of gneisses, their lateral variations, similarity to other gneisses obviously of other sections of the sequence, the emplacement of granitic rocks and acidic veins during several stages in the development of the gneisses as well as the gradational contacts between the different types of gneisses were found to be most perplexing. Earlier workers have had the same difficulties (c.f. Rogers and du Toit, 1908, p.63 and 65) and even when not mentioned, it is clear that in at least one case, the leptites were confused with the gneissic aplogranite. These difficulties can be resolved and by grouping various similar types of gneisses, a general stratigraphic sequence evolved during the present survey. However, gradational types of gneisses do present insurmountable difficulties and on the map such types are in some places grouped with other rocks and elsewhere they are shown separately.

Along broad lines the general sequence of the paragneisses is fairly simple and it is rather surprising that, though with multiple minor variations, the general succession is fairly constant over most of the area. The sequence as established for the present area is in agreement with that of the O'okiep area (Benedict, et al., 1964, p.246) and to the south of the area (Jansen, 1960, p.29), but in both cases it is thought that the repetition of similar lithological types is due to isoclinal folding.

The sequence as deciphered is as follows:

(Top)

6. A wide variety of mafic rocks, pyroxene granulites, orthopyroxene and hornblende-bearing gneisses and fine-grained biotite gneisses with minor white leptites in the east, but mainly fine-grained biotite gneisses with some amphibolites in the west.

5. White metaquartzites; widest distribution in the Komaggas area, but are not always present elsewhere and tend to thin and disappear towards the east where they are sporadically encountered as small lens-like bodies within the mafic rocks at or near their base. In some localities the quartzites are associated with minor lenses and bands of crystalline dolomite which also occurs without the presence of the quartzite in the same stratigraphic position. There appears to be only one position in the sequence where quartzites are encountered.

   In the southern part of the area, south of latitude 30°30'S, the place of the metaquartzites is taken by felspathic quartzites which are arkosic in places and are almost indistinguishable from the underlying leptites in places. Strong shearing of these rocks along the southern border of the area produced quartzites similar to those described above.

4. Cordierite-sillimanite gneisses, in places with garnet in the east, staurolite and muscovite schists in the west.

3. A thin band of pink to orange-weathering leptite occurs sporadically at the base of the paragneiss succession. When ortho-quartzites overlie the leptite, there is no difficulty in distinguishing these types and although only thin and most inconspicuous, it can nearly always be found when searched for.

2. Pink biotite gneiss, usually leucocratic with distinctive red-weathering; this unit occurs between the basal gneisses and the paragneiss sequence. On the map some of these red-weathering gneisses have been included with the basal gneisses where there is a tendency to develop augen and in other places where they are almost devoid of dark constituents, they have been included with the leptites. The pink gneisses only appear in the eastern part of the area and they increase fairly rapidly in thickness towards the east and south-east. In some places a thin and persistent pyroxene-granulite band occurs near the base of the pink gneisses.

(Bottom) 1. Augen gneisses, forming the base of the sequence known as the Nababeep gneiss in the O'okiep area, have been described in several published reports. Fairly wide variations in the size of augen and felspar porphyroblasts exist, and no floor to these gneisses has been found in the area investigated.

Where quartzites or prominent leptite bands are absent, the Nababeep gneiss near the contact becomes streaky and a banded nature is evident. The rock then encloses thin skialiths and lenses of mafic rocks. In the Koornhuis area (2917DD), the contact in several localities is often a zone which can only be described as granitic. In many places the contact is sharp, but not very obvious when the rocks of the paragneisses are also leucocratic, and the coarse gneiss rapidly becomes fine grained and strongly banded.

At Tweefontein (2918CD) and a little to the north, leptite and pink biotite gneiss are found overlying the above sequence, but it is clear that the repetition is due to isoclinal folding.

The rocks mapped as porphyroblastic granite gneiss occurring within the confines of a major synform along the northern edge of the Koornhuis area (2917DC and DD), north-east of Komaggas and also at Leliefontein and Eselsfontein (3018AC) presented problems of correlation. At Eselsfontein it is apparently intrusive as described below, but in the north the rock, although containing many mafic skialiths and clusters of garnet as remnants of digested mafic inclusions, appears to grade into the Nababeep gneiss and seems to represent a dark, coarse phase of that gneiss.

To return to the problem of correlation, if the quartzites found at Springbok, in the present area and farther south are to be correlated with the Kaaien quartzites, it is only natural to expect that the large thicknesses of mafic rocks underlying those rocks in the Richtersveld area and west of Prieska will have left some trace at the base of the succession here, especially since the other rock types are constantly encountered over such a wide region. The indications are that the Nababeep gneiss constitutes the floor on which the prototypes of the paragneisses accumulated and although it participated in the isoclinal folding of the rocks, so that disjointed relicts and bands of the paragneisses are found within the gneiss, nowhere was any feature which would be diagnostic of rocks underlying the Nababeep gneiss, ever found.

It is of interest to note the presence of aluminous rocks, staurolite and kyanite-bearing rocks in the west and sillimanite-cordierite gneisses inland, near the base of the paragneiss sequence, and the conclusions reached by Coetzee (1941a) must be considered. He has suggested that these rocks represent metamorphosed bauxite deposits and it is quite remarkable that the association of quartzites and aluminous rocks is constantly found in Bushmanland (De Jager and von Backström, 1961; De Jager, 1963; Coetzee, 1942). Serdyuchenko (1968) recorded similar occurrences from Norway, Australia, Russia, Madagascar and referred to the suggestion of Coetzee and assigned a similar origin to the rocks there. He also mentioned the baryte-hematite-quartz ores as indicative of metamorphosed older crusts of weathering and described a way by which barytes can be concentrated from the products of decomposition of felspars and micas. In a situation similar to the lithological setting of the aluminous rocks, Mathias (1940a) and Coetzee (1958) recorded the presence of barytes in northern Namaqualand.

It therefore does appear as if the presence of aluminous and baryte-bearing rocks of Namaqualand indicate a major break in the geological history of the area. Furthermore, the succession of paragneisses in the present area can almost certainly be correlated with rocks of Kheis age, but the quartzites and associated rocks here perhaps represent the basal part of the Kheis succession and the paragneisses as a whole represent a much reduced thickness of the so-called Kheis System.

C. ROCK TYPES

1. Nababeep gneiss

The rocks considered as representing the platform on which the sequence of paragneisses was deposited are typically brown-weathering, frequently porphyroblastic, coarse augen gneisses. In the area mapped these gneisses attain their widest distribution in the Koornhuis area (2917DC and DD), but also form the large spectacular exfoliation domes (Plate I) south of the farm Eendoorn, on Silverfontein and Hytkoras (2918CC). Farther south the gneisses become less prominent and lie in E-W striking ribs exposed between the paragneisses. In the southern part of the area they are absent, but are probably again exposed in the Bitterfontein area where they are described as biotite augen gneisses (Jansen, 1960). Similarly, in the north-western part of the area mapped, these rocks were not encountered.

The augen gneisses are known as the Nababeep gneiss in the O'okiep area and this useful name will be adhered to in this report (Söhnge, 1950; Benedict et al., 1964; van Zyl, 1967). The normal weathered surface of the gneisses is light brown, but on Silverfontein the rocks are distinctly grey while on Hytkoras, the large exfoliation domes are of an unusually dark brown colour. The gneisses show a number of variations due to the variable amounts of dark constituents present, degree of banding and the presence and sizes of porphyroblasts in addition to the augen. The freshly fractured surface of the Nababeep gneiss is grey and the compositional variations usually appear to have a tendency towards parallelism with the strike of the foliation. During the survey it was attempted to map wide darker zones in the gneisses, but they are not continuous over very long distances and merge with the ordinary augen gneiss.

The Nababeep gneiss is usually strongly foliated, most frequently of the augen type and felspar porphyroblasts, when developed, do not attain the sizes of crystals seen in the other types of porphyroblastic gneisses. The augen consist of flattened aggregates of quartz and felspar and the biotite, imparting the strong foliation to the rock, forms discoid aggregates, resulting in a streaky appearance of outcrops. The variation in the amount of biotite is evident even in the reports on the same area; Benedict et al. (1964, p.246) reported a characteristic biotite content of five to ten per cent while Strauss (1941, p.37) said that 28 per cent biotite is typical. He also (p.37-38) listed the minerals biotite, quartz, plagioclase, microcline perthite, apatite, magnetite-ilmenite, sphene, muscovite in order of abundance and described the rocks as sub-acid, peraluminous granodiorites. Judging by the position on the map of the samples collected by Mathias (1940), it is almost certain that at least specimen G 13 is a type of Nababeep gneiss and this is classified with those said to be normal potash granites. Mathias discussed

Plate I. Exfoliation dome of Nababeep gneiss on Stof Kraal looking south. Also shown are numerous east-west lines along which movement took place and north-south fractures

the mineralogy in great detail and it would suffice here to describe the variations encountered during the survey.

The gneisses at Silverfontein contain a small amount of hornblende and farther east towards Rietfontein, dark brown zones in these gneisses bordering on the contact with the mafic rocks form wide dark bands parallel to the contact. These dark zones have been found to contain a greater proportion of hornblende than elsewhere. Some of these bands have also been found to contain a little hypersthene, while those on the western side of Kameelboom (2917DD) contain some hypersthene as well as a little clinopyroxene in addition to hornblende and biotite. Except for being darker and perhaps more strongly banded, these rocks do not appear to be different from some of the variations encountered in the Nababeep gneiss, but they almost certainly represent infolded bands of the overlying mafic rocks. Darker zones have also been found in an area south of Namaras (2917DD) and again around Meskraal to the north of Kraaifontein (2917DC). In these places the Nababeep gneiss becomes so dark as to resemble the dark porphyroblastic gneisses. Strauss (1941, p.99) described discoloured gneiss in the O'okiep area as indicating unexposed noritoid intrusives. According to him, the discoloured gneiss is not due to the effects of thermal metamorphism as it is highly sericitised and contains much limonite.

When the rocks are sheared the augen become elongated and in some places the gneiss is strongly banded with biotite concentrated along very fine persistent lines separating the wider leucocratic bands and on the foliation planes fine aggregates of biotite impart a strong lineation to the rock. Under the microscope the effects of shearing are seen in the development of mortar structure and bent twinning lamellae and cleavage traces. In places quartz which normally shows undulose extinction, is recrystallised and the effect of strain is hardly noticeable.

At Mesklip (2917DD) the Nababeep gneiss tends to be granitoid and as a result the gneissosity is very vague or absent. Benedict et al. (1964, p.246) listed impersistent "granulites"* as occurring with the Nababeep gneiss. These thin bands of leucocratic rocks are common, usually parallel to the strike of the foliation of the gneiss and become so numerous in places that the assemblage simulates a very coarse migmatite. Such groups of thin leptites occur along a zone some kilometres south of Mesklip and Koornhuis (2917DD) and again west of Meskraal (2917DC) across the Buffels River.

Near the contacts with the overlying paragneisses (Plate II), the Nababeep gneiss tends to become granitoid and in places pods of leucocratic granitic rocks occur which merge with the underlying gneiss, but have sharp contacts with the paragneisses with which they are locally interbanded. At one locality east of Koornhuis the contact between the Nababeep gneiss and the overlying mafic rocks is exposed. Here the foliation of the Nababeep gneiss becomes wavy as the contact is approached and skialiths of mafic material appear and increase in number and eventually the rocks do not resemble the underlying gneisses at all. East of Kraaifontein (2917DC) a band of granitic rock forming a small ridge and containing garnets and lens-like inclusions of schist separates the Nababeep gneiss from the overlying schists, but the contacts between the granitic rock and adjoining formations on both sides are sharp. Farther west at Kraaifontein these rocks are nebulitic gneisses (Berthelsen, 1961, p.71) and show intrusive relationships with the mafic rocks.

* The term leptite is preferred for the quartzo-felspathic rocks in this report.

2. Paragneisses

(a) Psammitic gneisses

(i) Pink gneisses

Poldervaart and von Backström (1949, p.456) originally coined the term pink gneiss for a group of rocks by virtue of their distinctive red-brown weathered surfaces and since then other investigators have employed the name (Jansen, 1960; Kröner, 1968). In the mapped area the pink gneisses appear in the region between Kersbosch-fontein (3018AA) and Tweefontein (2918CD), and are again exposed in the most southerly parts (3018CC and CD). As the leptynites also weather to a red-brown colour some rocks shown to belong to the leptynites on the maps, should perhaps have been included with the pink gneisses. These occur in the Rooifontein area (3018AB) and farther south near Leliefontein (3018AC) and towards Roode Kloof Hoek (3018AD). However, the occurrence of a thin basal mafic band in several localities was the factor in deciding to include these rocks with the leptynites. Von Backström (1967, p.45) also found difficulty in distinguishing these gneisses from what he termed pink garnetiferous granulites. The pink gneisses also proved difficult in places as far as distinction from the Nababeep gneiss is concerned and those rocks south-west of Pedroskloof (3018AA) are in part also fairly leucocratic and red weathering.

The pink gneisses are predominantly fine grained but often grade into rocks with poorly developed augen and even varieties containing subhedral to euhedral felspar porphyroblasts. These rocks usually do not form topographically prominent features, but south-west of Kersbosch-fontein and farther west, outside the confines of the present maps, large exfoliation domes are built of the pink gneisses.

The rock collected at Tweefontein is gneissose, consisting of pink felspar and quartz with an evenly-distributed small amount of dark minerals. Some of the specimens collected elsewhere are distinctly banded. In thin section the pink gneiss is seen to consist of heteroblastic microcline microperthite, large anhedra of quartz showing undulose extinction, and small, usually somewhat dense, crystals of oligoclase. A little altered yellowish-brown biotite with some ore complete the mineralogical composition of the rock. In other specimens examined perthite as poikiloblasts with small rounded quartz grains is the main felspar. Zircon is present as comparatively large crystals in one of the rocks examined, while in another sphene forms coronas around some grains of ore. Sheared specimens of the pink gneiss have been found to contain crush zones with sericite, granulated quartz and a little calcite and epidote.

In the Paarde Hoek area (3018AA) these gneisses are migmatitic and contain skialiths and streaks of hornblende-pyroxene granulites and a little farther to the east an assemblage almost resembling an agmatite (Mehnert, 1968, p.8-9) with large blocks of mafic material, occurs within the pink gneiss.

Kröner (1968, p.167-183) correlated the pink gneiss with the Kaaien quartzite and convincingly showed that it most likely originated from sediments of arkosic composition.

(ii) Quartzo-felspathic rocks

Leptynites (Holmes, 1920, p.139), which can also be compared with what Poldervaart and von Backström (1949, p.456) term pink gneisses, are most conspicuous in the hills around Rooifontein (3018AB) and form prominent hills towards Boesmanplaat and again farther south between Leliefontein (3018AC) and Platbakkies (3018AD) and are also very prominent in the hills between Remhoogte (3018AD) and Draaihoek (3018CB).

These rocks are usually medium grained, granulose, pink in colour and weather to a reddish-brown colour. When they are sheared, they show indistinct banding, but the leptynites can become fairly coarsely crystalline and in places even have small pink subhedral felspar porphyroblasts. The rocks contain a small amount of dark minerals, usually fairly evenly distributed throughout the rock.

Under the microscope the rock is seen to have a heteroblastic texture and consists of large poikiloblasts of microperthite containing small rounded grains of quartz. Quartz is also present as large and small anhedra, in some cases lenticular, showing undulose extinction. Plagioclase is usually a minor constituent of the leptynites thereby distinguishing them from the leptites. Plagioclase is usually densely altered, while one specimen examined contains sericite, epidote and calcite as alteration products.

Small flakes of brown biotite are the usual dark constituents found in these rocks. The biotite is usually somewhat chloritised and is most frequently found in aggregate with ore minerals. Occasional flakes of muscovite are seen and all or some of apatite, zircon and sphene occur as accessory minerals. One specimen examined contains sparsely distributed small grains of garnet.

The leptites occur near the base of the paragneiss sequence in the south-eastern part of the area where they are underlain by an increasing thickness of pink gneisses, but to the west they occur sporadically at the base of the metasedimentary sequence. In some localities the leptites are topographically prominent such as in the synform of Silverfontein (2918CC), but otherwise they are easily overlooked because of the similarity to thin quartzo-felspathic bands in the gneiss. However, when the band of leptite is specifically searched for, it can usually be found, especially in the eastern part of the area.

To Benedict et al. (1964) these rocks are known as granulites and Strauss (1941, p.35) confused them with the granitic gneisses which they certainly resemble. Pike (1959, p.20) described these rocks in detail and following Jansen (1960), called them aplo-gneisses. He found them in the same stratigraphic position as Benedict et al. (op. cit., p.246) and Söhnge (1950, p.932), a position which has been clearly confirmed during the present survey. Pike described the contact between the leptites and the overlying metasediments as gradational, while the contact with the underlying gneiss is gradational in some localities and sharp elsewhere. In the present area the contact between the leptites and Nababeep gneiss is gradational. On approaching this contact east of Komaggas, the Nababeep gneiss becomes more leucocratic and finer grained and in this way the transition from one type of rock to the other is gradual. The transition zone from gneiss to leptite in the Drooge Daap area (2917DD) is no more than two metres wide. Pike (op. cit., p.24) also listed the differences between the metaquartzites and his aplogranite and must have had the same difficulties experienced during the present survey in distinguishing between the rocks in the Menschlief area (3018CD). As the leptites are for the most part thin and sandwiched between pink gneisses and metaquartzites, there can hardly be any doubt that they represent metamorphosed felspathic sandstones.

(iii) Felspathic quartzites

The quartzo-felspathic rocks and pink gneisses grade into felspathic quartzites in the low ridges in the southernmost part of the area mapped. These rocks occur from Zout Rivier (3018CC) in the south-west and they lie below the quartzites across Louws Cyfer and farther east and again in the same stratigraphic position in the low hills on the farm Bitterfontein. They appear as inliers below the rocks of the Nama Formation farther east and form the hills at Menschlief (3018CD) and farther north. South-east of Garies they have been intruded by granite and lie as rafts in the granite and attain wide distribution in the area east of Garies on sheets 3018AB, AC and AD, but in the most northerly parts and to the north-west they are infrequently represented and their place is mostly taken by fine-grained biotite gneisses. Their main distinction in the field from the underlying leptites is in colour difference, amount of quartz present and that they are usually overlain by metaquartzites. The felspathic quartzites are often interbanded with mafic rocks, they are usually finer grained than the leptites, banding is more distinct, and pegmatitic stringers are finer grained and conformable with the banding whereas the pegmatites in the leptynites and leptites tend to be coarse and generally cross-cutting. Some of the felspathic quartzites become more coarse grained, they appear to contain a greater proportion of felspar and tend to weather to a darker colour.

Usually the rocks are somewhat flaggy, hard with fine banding, fine grained and sugary-textured. In some places they are friable and the freshly-fractured surface is light greyish to buff and usually lustrous. They weather to a light-brown to greyish-brown, finely pitted surface on which the banding is more pronounced. In thin section they display large, usually lenticular anhedra of quartz in a granoblastic matrix of almost equidimensional grains of felspar and quartz. The felspar content consists of microcline, microcline-microperthite and perthite with some plagioclase which is usually oligoclase, but in one specimen was determined as andesine. Antiperthite is common as well as a little myrmekite.

Brown biotite, some of it showing greenish alteration, is a common constituent of all these rocks, but occurs in minor amounts except where the host grades into biotite gneisses towards the north. Several of the specimens collected contain small pink garnets while iron ore, in some specimens rimmed by chlorite, and zircon are the usual accessories. One specimen collected west of Platbakkies (3018AD) was found to contain a little hypersthene and some sphene. Shearing in these rocks often result in the development of greenish tinges as a result of the formation of epidote. A specimen from south-east of Garies was found to have thin bands of sericite containing aligned acicular crystals of sillimanite. Next to the granite at Rietpoort (3018CC) the felspathic quartzites are distinctly mottled, a feature found to be due to decussate aggregates of chlorite.

(iv) Metaquartzites

The metaquartzites are the most useful marker beds in the area and assist greatly in the deciphering of the succession and structure. Although they are thin, they form topographically prominent ridges which can easily be recognised from afar and on aerial photographs. Their presence results in the ridges in the southernmost part of the area mapped and are again prominent in the west. Elsewhere there are several lenticular bodies of metaquartzite, too small to show on the map, occurring at or near the base of the paragneiss sequence. They are isoclinally folded in the hills of Koornhuis beacon (2917DD)(Fig.1) and are responsible for the prominent hills around Komaggas where they are interfolded with the schistose rocks. Farther to the north-west they occur in isolated hills north of the Buffels River and continue to the north in continuous steep-sided ridges which eventually reach into the Richtersveld. Where they abutt against the rocks of the Stinkfontein Formation, they are indistinguishable from the orthoquartzites of the lower part of that formation.

The metaquartzites are massive, coarsely crystalline and milky white and in places have schistose or flaggy intercalations due to shearing. In the west a lower member of ferruginous brown

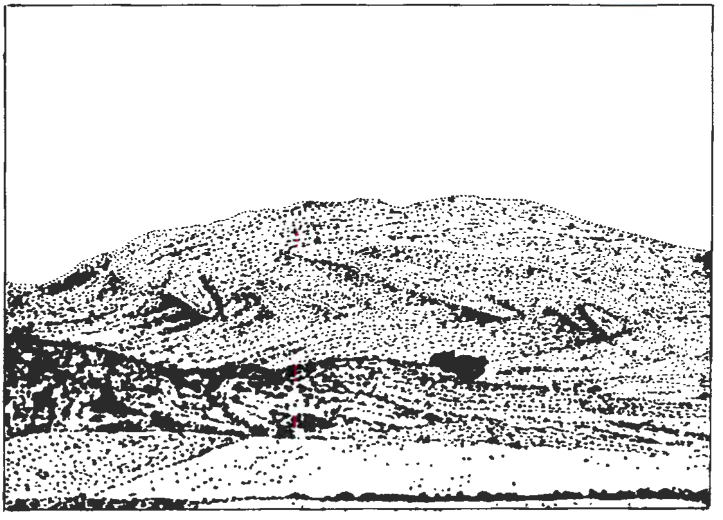

Fig. 1. Isoclinal folding (F_2) of metaquartzites seen in Koornhuis hill when viewed from the east

quartzite is present in some localities while a light blue metaquartzite is occasionally found. Strauss (1941, p.26-27) described milky quartzite with minor schistose intercalations and bands of arkose in which intraformational unconformities, ripple marks and suggestions of crossbedding can be seen. Structures which could without doubt be ascribed to original sedimentary features were never seen during the present survey.

Benedict et al. (1964, p.246) record a thickness of 50-400 ft. for the Springbok quartzite and Strauss (op. cit., p.18) found variations between 3 ft. and 200 ft. of solid quartzite. In the much larger area mapped now, the metaquartzites are either absent or relatively thin and only attain the great thickness at Komaggas because of repetition due to folding in that area. Strauss (p.21-22) described the quartzites as being conformable with the gneiss, a feature which he ascribed to complete recrystallisation of the quartzite considered to be older than the gneiss.

De Villiers and Söhnge (1959, p.34) divided the Kaaien Series found in the Richtersveld into two stages and further substages, the descriptions of which do not bear any resemblance to the metaquartzites of the present area. Gevers et al. (1937, p.26) also correlated the quartzites in the area to the north of Springbok with the Kaaien quartzite, listed evidence for its sedimentary origin and noted that the quartzite closely resembles the quartzose rocks of the Springbok area. They (p.27) also recorded the presence of conglomerate in the quartzites.

On the farm Bitterfontein (3018CC and CD) in the southern part of the area now mapped, the contacts between the felspathic quartzites and the metaquartzites are sharp and in that part of the area the metaquartzites appear to have resulted from the shearing of the felspathic types and farther east of Menschlief and Guaapseberg (3018CD) the rocks mapped as quartzites are somewhat felspathic and were at first confused with the leptites. In places the metaquartzites have been intruded by porphyroblastic gneissic granite (granodioritic) and several large xenoliths are found within the granite. In the western part of the area mapped, the contacts between the metaquartzites and adjoining rocks are always sharp whether they are the underlying staurolite schists or overlying mafic gneisses.

Under the microscope the metaquartzites are seen to have heteroblastic textures and to consist of quartz lenticles with lobate edges. The lenticles are elongated parallel to the foliation and always display undulose extinction which is frequently columnar. Usually the rocks contain dense, unevenly distributed patches of sericite which locally show yellow or red iron staining. When the rocks are banded the other minerals, mostly iron ore usually with a little zircon, apatite, garnet, muscovite and rare biotite, occur along thin bands alternating with bands of more coarsely granular quartz. Banding is also produced by alternating finer grained granulated quartz and bands of coarse anhedra or by thin lines of sericite traversing the rocks. The metaquartzites in many cases weather to a red colour due to the oxidation of the iron content, while others are red or brown and contain interstitial limonite. One specimen from near Nana beacon (2917AB) was found to contain kyanite in addition to muscovite. A brown translucent quartzite from Witkliphoogte (2917AD) with dark vein-like patches contains lenticular aggregates of fine garnets which show elongation parallel to the columnar extinction of the quartz. In addition to these minerals, the quartzite also contains small flakes of biotite, chlorite, rounded grains of magnetite and a little apatite. An interesting garnetiferous quartzite, also from Witkliphoogte, is reddish brown in colour due to the presence of fairly large garnet insets in a white quartzitic matrix. In thin section the porphyroblasts of garnet are seen to contain numerous elongated grains of quartz, some densely altered felspar, and the garnets are cracked parallel to the elongation of the quartz inclusions.

Pike (1959, p.17) found that blue colouration is due to finely disseminated ferruginous material, but in the present area blue metaquartzite is rare and the colour is not due to iron. One specimen from Harras (2917AD) consists of poikiloblastic quartz containing plagioclase, dense sericitic patches, small flakes of green biotite and a little garnet while a distinctive deep blue metaquartzite from the farm Oranjefontein north of the present area and north of Platjes Fontein (2918CC) contains aggregates of spinel in quartz. The cores of the aggregates and the larger crystals are of a green variety of spinel grading into and mantled by blue spinel which appear almost violet under the microscope. The groundmass consists of crushed and recrystallised quartz containing aggregates of granules of hematite.

(v) Graphite-quartz schists

Graphitic schists have been found in such widely separated areas as in the far south on the farm Bitterfontein (3018CD), in the west of Kraaifontein and Wildepaarde Hoek (2917DC) and on Steenbok (2917AC) in the north-west. These rocks were always encountered in the same position in the sequence; usually just below the metaquartzite or felspathic quartzites, but where these rocks are absent, the graphitic schists are found with the aluminous schists.

The graphitic schists are grey, banded to schistose, fine grained and shimmering with numerous small shiny flakes of graphite imparting the foliation to the rock. They are red to yellow weathering and in thin section are seen to consist of equigranular quartz with numerous flakes of graphite showing distinct preferred orientation. In one specimen collected, fine sericite forms the matrix to fragments of quartz and graphite flakes surrounded by fine pellets of oxidised iron ore. The rocks frequently contain patches of opal; red-brown biotite and muscovite are present in variable amounts, while the specimen from Wildepaarde Hoek also contains some sillimanite.

(vi) Magnetite-bearing rocks

In the area to the south-east of Garies there are several lens and pod-like occurrences of magnetite-rich rocks. These bodies appear to lie at the base of the paragneiss sequence, but it is not possible to be positive of their stratigraphic position as much granite has been intruded into the paragneisses there. As the rocks consist mostly of quartz and magnetite, thin sections are not available, but they are known to contain monazite. Spectrographical analyses kindly conducted in the laboratories of Anglo American Corporation have yielded 5,605 p.p.m. Th for a specimen collected on the road between Garies and Doornkraal and 1,417 p.p.m. Th for the rock from the ridge south of Wilgehout Fontein (3018CA). A similar specimen collected in the Vanrhynsdorp district south of the present area was found to contain more than two per cent ZrO_2. The monazite from Stoffelsfontein (subdivision of Buffelsfontein, 3018CA) has been dated as 920±30 My (Nicolaysen and Burger, 1965).

(b) Pelitic gneisses and schists

Rogers (1904) first found and described sillimanite-cordierite schists in Namaqualand and later (Rogers, 1915, p.75) found the staurolite schists east of Port Nolloth and also near the mouth of the Buffels River. Strauss (1941, p.29) mentioned schistose and argillaceous rocks as occupying a definite stratigraphic position in the geological sequence at O'okiep. Brink (1950, p.127-144) described the petrography of hornfels and cordierite-garnet para-gneisses occurring in the Bitterfontein area in detail and correlated them with rocks of the Kheis "System". From the same area Jansen (1960, p.19) found cordierite-biotite-garnet gneiss and granulite as well as cordierite-sillimanite hornfels. Von Backström (1961, p.33) recorded kinzigites from the Keimoes area of which the analyses and modes are given. Coetzee (1941, p.201-203) noted the presence of sillimanite-corundum rocks of the Pella area and considered them to be metamorphosed bauxites. Later he (Coetzee, 1958, p.19) found such a considerable number of sillimanite-bearing rocks that an aluminous "horizon" was postulated. He envisaged local accumulation of alumina-rich material along a certain zone within the original sediments. De Jager and von Backström (1961, p.7) found that all the deposits of sillimanite examined by them, with one possible exception, occur in mica schist underlying the metaquartzite.

In the present area aluminous rocks occur at the base of the mafic part of the sequence and when metaquartzites are present, the succession is the same as that found by previous investigators. In most of the present area the aluminous rocks are represented by cordierite-sillimanite gneisses while towards the coast, west of the escarpment, their place is taken mainly by staurolite schists underlying the metaquartzites.

(i) Cordierite gneisses and cordierite-sillimanite gneisses

These rocks show a wide variety of colours being black, dark grey, greenish grey, grey, light grey, brownish grey and brown. They are fine, medium or fairly coarse grained, massive, poorly banded to distinctly banded, frequently strongly lineated and even in some cases somewhat schistose. Banding is more pronounced on the rough, weathered surfaces which can be light brown, brown, brownish grey or black. The lenticular mineral aggregates, especially patches of garnet, result in a streaky to gneissose structure. In places in the Komaggas area, the schists are much altered to fine white, yellow or red kaolinitic rocks, some with remnants of quartz.

In thin section the texture of these gneisses is seen to be heteroblastic and they are composed of quartz, cordierite, sillimanite, garnet, potash felspar, plagioclase, biotite, iron ore, spinel, zircon and in some instances apatite. Sericite is a frequent alteration product.

Quartz occurs as variably-sized anhedra showing undulose extinction and in some rocks contains small acicular inclusions. Banding is seen in one specimen where quartz forms the matrix along zones alternating with bands in which cordierite is the groundmass. Cordierite, often distinctively twinned and containing small zircon crystals with pleochroic haloes, is usually diablastic enclosing numerous rounded grains of quartz, small flakes of biotite, trains of sillimanite, magnetite and pyrite. The cordierite is usually much altered to pinite, which always forms around inclusions of ore.

Sillimanite occurs as equant idioblasts or as acicular crystals, usually enclosed in cordierite. In one thin section examined, sillimanite is enclosed by all other minerals, but is vermicularly intergrown with cordierite. The largest crystals of sillimanite are usually associated with ore which are rimmed by coarse sillimanite (Fig. 2). Sillimanite is also associated with biotite and enclosed by biotite. Sillimanite needles are frequently bent.

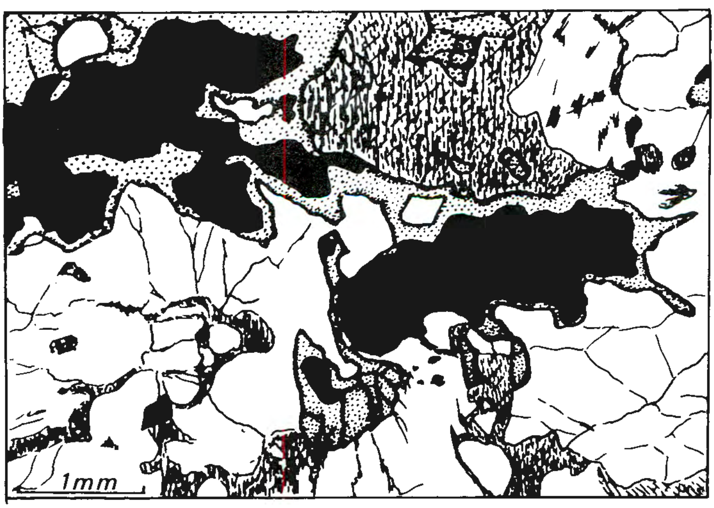

Fig. 2. Sillimanite (stippled) mantling ore (black) in a cordierite-sillimanite gneiss from Louws Cyfer

Biotite is of a red-brown variety, rarely showing greenish alteration and when associated with sillimanite, it is orientated parallel to the trains of sillimanite, but elsewhere the flakes are arranged at an angle to the foliation, while lenticular garnet aggregates have the same orientation as the sillimanite. In one thin section examined biotite flakes show strong preferred orientation which is not adhered to by sillimanite, but when these minerals are enclosed by cordierite, they have the same orientation. In other rocks the biotite flakes lying across the banding have been bent. Garnet is usually diablastic and contains ore, biotite, quartz and some spinel. In some specimens it is intergrown with biotite and quartz, or rims iron ore and even spinel. Rarely garnet occurs as idioblastic crystals.

In some of these rocks potash felspar is absent, but it can also be one of the major constituents and is represented by microcline, perthite or microcline microperthite. This felspar shows bending of cross-hatching and diablastically encloses quartz, small sillimanite needles and flakes of biotite. A little myrmekite is seen in some of the thin sections. Plagioclase is normally a very minor constituent in the gneisses and varies in composition from oligoclase to labradorite. Only in one thin section does plagioclase constitute a major component and there it occurs as equidimensional anhedra showing bent twinning lamellae and uneven extinction.

Table 2. Mineral assemblages of the cordierite gneisses and cordierite-sillimanite gneisses

Specimen No.	Cordierite	Sillimanite	Quartz	Biotite	K-felspar	Garnet	Plagioclase
284	x	x	x	x	x	x	x
293	x	x	x	x	x	x	x
317	x	x	x	x	x	x	x
320	x	x	x	x	x	x	x
650	x	x	x	x	x	x	x
322	x	x	x	x	x		x
349	x	x	x	x	x		x
440	x	x	x	x	x		x
120	x	x	x	x	x		
645	x	x	x	x	x		
67	x	x		x	x	x	
271	x	x	x	x		x	x
272	x	x	x	x		x	x
273	x	x	x	x		x	x
56	x	x	x	x		x	

(Table 2 continued)

Specimen No.	Cordierite	Sillimanite	Quartz	Biotite	K-felspar	Garnet	Plagioclase
140	x	x	x	x		x	
156	x	x	x	x		x	
157	x	x	x	x		x	
158	x	x	x	x		x	
196	x	x	x	x		x	
108	x	x		x			x
649	x	x	x	x			
240	x		x	x	x	x	x
250	x		x	x	x	x	x
412	x		x	x	x	x	x
241	x		x		x		x
641	x		x		x		x
57	x		x	x		x	

(ii) Muscovite-quartz schists

The muscovite-quartz schists only attain fairly wide-spread distribution around Grootmis and are usually white shimmering schistose rocks, but they vary in colour from brown, grey to black, depending on the amount of biotite present. Some specimens are stained reddish due to the oxidation of iron ore while some are distinctly banded with alternating micaceous and quartzose or felspathic bands and are rarely found containing felspar porphyroblasts. Lineation is frequently strongly developed as imparted by biotite aggregates and when these rocks contain garnets, the weathered surface is rough and nodular.

In thin section the rocks are seen to consist of a granoblastic matrix of angular grains of quartz which in some rocks form bands or lenticular aggregates alternating with fine-grained, well-orientated flakes of muscovite. Where felspar is present the texture of the groundmass is heteroblastic.

Muscovite is usually found to be of two generations; the fine-grained flakes occur in bands dimensionally orientated parallel to the schistosity while larger flakes lie across the banding. The latter flakes are in many cases seen lying along axial planes of later folds. Bands of fine muscovite curve around aggregates of biotite with which the larger flakes of muscovite are often associated.

Red-brown, in some cases greenish, biotite usually shows a tendency for dimensional orientation parallel to the muscovite bands, but frequently lies across the foliation or forms aggregates of flakes showing no preferred orientation.

These schists usually contain some garnet which usually forms large diablasts. The garnets lack crystal faces and in one specimen lenticular inclusions of quartz and small flakes of muscovite in the garnet lie with their longer dimensions at an angle to the schistosity. The garnets in some rocks are cracked with quartz and chlorite occurring along the cracks. Chlorite is also found as an alteration product of biotite or in aggregate with iron ore. Ore, usually with oxidised rims, is the common accessory mineral, apatite and zircon are frequently found as few small crystals, while sphene was seen in two thin sections examined, in one of which the sphene occurs as small metacrysts along biotite-rich bands. Small grains of epidote are rarely present.

Felspar is not a usual constituent, but plagioclase as anhedral crystals in the groundmass, is the most common felspar encountered, while some perthite and microcline as fairly large anhedra are present in some of the rocks. Microcline forms large porphyroblasts in one of the schists.

Table 3. Mineral assemblages of the muscovite-quartz schists

Specimen No.	Muscovite	Biotite	Quartz	Garnet	Plagioclase	K-felspar	Chlorite	Epidote
560	x	x	x	x			x	x
391	x	x	x				x	x
593	x	x	x			x		x
556	x		x			x		x
390	x		x			x		x
596	x		x		x	x	x	
512	x	x	x	x			x	
503	x	x	x	x			x	
526	x	x	x		x	x		
389	x	x	x			x		
571	x	x	x	x	x			
457	x	x	x		x			
583	x	x	x		x			
491	x	x	x	x				
581	x	x	x					
396	x		x					

(iii) Staurolite and kyanite-bearing schists

Staurolite schists have their widest distribution in the antiform adjoining the shear zone across the farm Steenbok (2917AC and AD), but the metacrysts of staurolite attain their largest size behind the homestead on Nakanas farther to the west. Other small occurrences have been found along the Buffels River at Bontekoe (2917CB) and Dikgat (2917CA), between Steenbok and Nakanas and in the north on Hardevlakte (2917AA) and between Nanassen and Grasvlakte (2917AB). Rogers (1915) reported the occurrence of staurolite schists on the coast, just south of the mouth of the Buffels River and he (op. cit., p.75) remarked on the fact that the long staurolite crystals lie in various directions across the schistosity and concluded that they were developed subsequent to the shearing responsible for the formation of the schists.

These schists are much like the muscovite-quartz schists described above except that they contain metacrysts of kyanite and staurolite. The kyanite crystals are usually seen to lie in the plane of foliation, imparting a distinct lineation to the rock, while the staurolite is most frequently seen to have crystallised across the foliation.

In thin section the staurolite-kyanite schists are seen to consist of the same minerals with the same relationships as those of the muscovite-quartz schists, but for the presence of kyanite and staurolite.

Kyanite usually occurs as fairly large diablastic subhedral crystals enclosing quartz and ore, and the enclosed minerals show elongation across the length of the kyanite crystals. In one specimen kyanite is seen forming aggregates of poorly orientated laths forming bands curving around garnet diablasts.

Staurolite forms idioblasts which are diablastic in some rocks containing small grains of quartz. They are most frequently found to lie across the foliation, but in other cases tend to lie lengthwise along the plane of schistosity. The bands of muscovite curve around the idioblasts of staurolite which, when they are large, show distinct zoning, with the cores dense with tiny inclusions. In two of the specimens examined the staurolite diablasts enclose small grains of garnet.

Plagioclase is seldom seen and contains poikiloblastic inclusions of quartz, apatite and tiny flakes of muscovite. Only one specimen examined contains sillimanite in addition to kyanite and staurolite. The sillimanite occurs with muscovite as sheaves of fine needles in the thin schistose bands across the rock. The banding is much disturbed by the formation of large crystals and curves around the kyanite while staurolite is clearly later than the kyanite. Garnet, usually diablastic, rarely forming idioblasts, in places dense with included ferruginous pellets, encloses flakes of muscovite and biotite, grains of quartz and kyanite. Garnet is also seen intergrown with the micas or with kyanite and is itself enclosed by staurolite.

An unexpected exception of a kyanite-sillimanite-bearing rock occurs in a locality on the farm Drooge Daap (2917DD). This rock is black-weathering, fine grained, shimmering and red in colour. Under the microscope it is seen as consisting of pink equidimensional subhedral crystals of garnet forming clusters or skeletal crystals in a mosaic of clear quartz with occasional small anhedral crystals of kyanite and a little fibrolite as tufts of very fine needles. In this rock, which is the only occurrence of kyanite east of the escarpment, there is a fairly large amount of iron ore and accessory apatite and zircon.

Table 4. The mineral assemblages of the staurolite and kyanite-bearing schists

Specimen No.	Muscovite	Biotite	Quartz	Garnet	Staurolite	Kyanite	Sillimanite	Plagioclase	Chlorite	Epidote
359	x		x	x	x	x	x		x	
501	x	x	x	x	x	x		x	x	x
516	x	x	x	x	x	x		x		
463	x	x	x	x	x	x				
524	x	x	x	x	x	x				
386	x	x	x	x		x		x	x	
387	x	x	x	x		x			x	
535	x	x	x	x		x			x	
492	x	x	x	x	x				x	
507	x	x	x	x	x				x	
620	x	x	x	x	x				x	
357	x	x	x		x					
490	x	x	x		x					
464	x				x			x		

(c) Semipelitic gneisses

The fine-grained biotite gneisses enjoy the widest distribution of all the paragneisses. They are especially widespread north of the Buffels River on the coastal plains west of the escarpment. In places they are comparatively leucocratic, but are then distinguished from the other biotite gneisses in being finer grained and usually finely banded. Usually they are red-weathering, dark grey rocks, some almost black, having a streaky or more often, finely banded and even schistose nature. When the rocks are not banded they are granulitic with an even distribution of fine-grained dark minerals, finely spotted in places, and elsewhere they develop small unobtrusive felspar porphyroblasts. The banded nature is usually more pronounced on weathered surfaces than in the freshly fractured rock. Migmatitic banding is fairly frequently encountered while a dark greenish gneiss with poorly developed augen occurs near the base of the mafic gneisses in places between Pedroskloof (3018AA) and Eselsfontein (3018AC). Numerous bands of pyroxene granulite and hypersthene-bearing gneisses occur within the fine-grained biotite gneisses especially in the mafic belt from west of Kameelboom (2917DD) to Bodabeep (2918CD). Along this zone it is thought that the highest part of the succession of the paragneisses has been preserved and here the biotite gneisses include leucocratic, almost white, bands consisting of antiperthetic oligoclase and quartz only, not encountered elsewhere in the area. The granodioritic porphyroblastic gneisses described below have been formed from these rocks while some of the biotite gneisses are highly magnetic and in these bands and lenses the magnetite can be detected with the unaided eye.

Microscopically the rocks are found to be very uniform in composition, consisting of heteroblastic, rarely granoblastic, matrices of quartz and felspar with fine bands of greenish brown biotite often associated with much iron ore. Oligoclase, more rarely andesine, is the main felspathic constituent, but microcline, microperthite and microcline microperthite may also be important constituents. The felspars are in most cases densely saussuritised or sericitised while quartz forms lenticular aggregates in banded specimens. The porphyroblasts are mostly microperthite, but in some specimens they are antiperthite and in one rock from Dikdoorn (3018CA) large plates of albite are present. Myrmekite was noticed in some of the thin sections and the twinning lamellae of plagioclase are frequently bent.

The amount of biotite present determines the colour index of the rocks and was found to be very variable. The flakes of biotite are usually well orientated imparting the foliation to the rock and are frequently seen to contain sagenitic webs of rutile.

Muscovite is not usually present, but has been seen interleaved with biotite. A distinctive feature of the fine-grained biotite gneisses is the comparatively larger amounts of the accessory minerals apatite and zircon. Sphene is also found, most frequently as rims to ore minerals or as tiny clusters in biotite bands, while rutile and fluorite are rarely seen. The alteration products found in these rocks are usually epidote, chlorite and sericite.

In six of the 28 thin sections examined garnet was found. It occurs as diablastic anhedra with inclusions of biotite and quartz and alters to chlorite. A specimen from near the mouth of the Buffels River was collected from the thin aureole around the granite intruded into mormal fine-grained biotite gneiss there. In this rock biotite is entirely absent and its place is taken by small scattered garnets while the whole rock, consisting of a fine granoblastic matrix of quartz and felspar, also contains numerous small pellets of iron ore

3. Mafic rocks

The mafic rocks include a wide variety of types and the most interesting mineral assemblages are encountered amongst them. They are present in all parts of the area mapped and overlie the quartzites and quartzo-felspathic rocks in the sequence. They, together with the fine-grained biotite gneisses, are considered to form the uppermost part of the paragneiss succession of Namaqualand, but in places are apparently overlain by quartzo-felspathic rocks and augen gneisses because of inverted successions.

(a) Amphibolites

Amphibolites are not as common as was expected when the present survey commenced. These rocks are usually found as sheaths to bands of granulites or as bands in granulites and the greater majority of them must have been derived by retrogressive metamorphism of the granulites. The amphibolites range in colour from light greenish grey, dark grey to almost black and are usually fine grained to very fine grained. They are granulose with evenly distributed equidimensional aggregates of dark minerals, or banded and even schistose when strongly sheared. Banding is seen as leucocratic bands, usually coarser grained, alternating with fine-grained mafic bands or by bands showing variations in the degree of coarseness of crystallinity. Lineation is in places distinctly imparted by the dimensional orientation of amphibole crystals. Sheared amphibolites are fissile with shimmering micaceous foliation planes and some of the more massive varieties contain small pink or white felspar porphyroblasts.

Under the microscope the texture of the groundmass of these rocks is seen to be heteroblastic, rarely granoblastic, and they consist of quartz and felspar with the mafic minerals usually concentrated in bands. Quartz occurs as large and small strained anhedra with lobate edges, often in lenticular grains which lie with their longer dimensions parallel to the banding. Quartz is present only as a secondary product in some of the rocks.

Plagioclase is usually andesine, but oligoclase and labradorite have also been determined in some of the thin sections examined. In one of the porphyroblastic types, antiperthite forms the porphyroblasts, while they are most commonly formed by perthite, but microcline and microcline microperthite have also been found. The twinning lamellae of the plagioclase are often bent, and this mineral is in some cases diablastic containing small rounded grains of quartz. Myrmekite was encountered in only one of the rocks and the felspar, especially potash felspar, are often much altered.

Brown to greenish hornblende is the common dark mineral present in the amphibolites and in those collected on the coastal flats west of the escarpment, bluish-green amphibole is found together with the usual hornblende. Large crystals of hornblende are anhedral while the smaller crystals often have some crystal faces developed. These crystals usually display a marked preferred orientation.

Brown to greenish brown biotite is often present and in sheared varieties, the mineral is abundant and is seen to form at the expense of amphibole. Some of the biotite has sagenitic rutile webs.

Epidote is also commonly found in clusters of small grains, but in one specimen which also contains zoisite, it is present as subhedral columnar crystals with dimensional orientation coinciding with that of the hornblende.

Ore minerals, zircon and apatite are common accessory minerals. Hematite is more frequently found in the amphibolites than in the other types of mafic rocks while sphene is nearly always present and most frequently mantling ore minerals and in one section even encloses biotite.

Pale green to strongly pleochroic chlorite is abundant in some samples, and is most frequently found to border on ore minerals. A little secondary calcite occurs in one of the thin sections examined.

In the table below the mineral assemblages commonly encountered in the amphibolites examined under the microscope are listed.

Some of the amphibolites contain fibrous alteration products yielded by the alteration of pyroxene. In a number of specimens clinopyroxene occurs as well as alteration products which can almost certainly be related to the alteration of hypersthene. The clinopyroxene occurs in colourless to pale green, anhedral to subhedral, rarely euhedral crystals which frequently show peripheral fibrous alteration. The rocks containing clinopyroxene nearly always exhibit a granoblastic texture.

Table 5. The mineral assemblages of the amphibolites

Specimen No.	Amphibole	Biotite	Plagioclase	K-felspar	Quartz	Epidote	Chlorite
291	x	x	x	x	x		x
207	x	x	x	x	x	x	
327	x	x	x	x	x		
402	x	x	x	x	x		
410	x	x	x	x			
148	x	x	x		x	x	x
215	x	x	x				x
287	x	x	x				
380	x	x		x	x	x	
445	x	x			x	x	
475	x		x	x	x		
437	x		x	x		x	
384	x		x		x	x	
497	x		x		x	x	
341	x				x	x	x
214	x					x	x

Scapolite was found in only one locality on the farm Kersbosch-fontein (3018AA) and it occurs in the pyroxene-bearing amphibolites as patches of fine-grained subhedral crystals. Jansen (1960, p.20) and Brink (1950, p.144-146) described similar rocks as occurring to the south of the present area, and to the north-east von Backström found similar rocks to enjoy a wide distribution in the area around Keimoes.

Table 6. The mineral assemblages of some of the pyroxene-bearing amphibolites

Specimen No.	Clinopyroxene	Amphibole	Plagioclase	K-felspar	Quartz	Biotite	Muscovite	Epidote	Chlorite	Scapolite
174	x	x	x	x	x	x			x	
404	x	x	x	x	x	x				
60	x	x	x	x	x					
81	x	x	x	x	x					
116	x	x	x				x	x	x	
421	x	x	x					x	x	
339	x	x	x			x				
416	x	x	x			x				
59	x	x	x							
285	x	x	x							
305	x	x	x							
446	x	x			x	x	x	x		
405	x	x			x	x			x	
350	x	x			x			x		
226	x	x			x					
369	x	x			x					
134	x	x					x			x

(b) Granulites

(i) Pyroxene granulites

Brink (1950, p.116-123) described norites occurring in the area mapped by him and discussed their petrography in very great detail. He distinguished the so-called norites consisting essentially of basic plagioclase, hypersthene and biotite from the granulites in which the plagioclase is more acid and is associated with hornblende or clinopyroxene and quartz, but also found elongated xenoliths of pre-granitic biotite-bearing norites. During the present survey it was found that most of the rocks described as norites by Brink occur within the mafic sequence and wide bands stretching for some kilometres are thought to represent metavolcanics rather than separate intrusive bodies. There are without doubt many small isolated meta-intrusive bodies as well as mafic sheets which now have the composition of norites and bojites, but with metamorphic textures and these are described below.

Similar rocks are found towards the east in the Keimoes area (Poldervaart and von Backström, 1949, p.441-444) and have been described as "earlier basalts and norites", but farther north (von Backström, 1967) and farther west towards and in the Richtersveld (von Backström and de Villiers, in the press; de Villiers and Söhnge, 1959) rocks indicating such a high grade of metamorphism apparently do not occur.

The granulites are usually dark grey, fine-grained granulose rocks and their weathered surfaces are rough and dark brown. They are in some cases vaguely or, more rarely, distinctly banded with colours ranging from light grey to almost black.

Under the microscope they are seen to be remarkably fresh and have granoblastic textures.

Table 7. The mineral assemblages of the pyroxene granulites

Specimen No.	Orthopyroxene	Clinopyroxene	Hornblende	Biotite	Plagioclase	Quartz
123	x	x	x	x	x	x
292	x	x	x	x	x	x
340	x	x	x	x	x	
417	x	x	x	x	x	
122	x	x	x	x	x	
406	x	x	x	x	x	
338	x	x	x		x	x
68	x	x	x		x	
88	x	x	x		x	
278	x	x	x		x	

(Table 7 continued)

Specimen No.	Orthopyroxene	Clinopyroxene	Hornblende	Biotite	Plagioclase	Quartz
418	x	x	x		x	
420	x	x	x		x	
432	x	x	x		x	
70	x	x		x	x	x
266	x	x		x	x	x
330	x	x		x	x	x
337	x	x		x	x	x
87	x	x		x	x	
189	x	x		x	x	
195	x	x		x	x	
401	x	x		x	x	
441	x	x		x	x	
455	x	x		x	x	
260	x	x			x	x
83	x	x			x	
206	x	x			x	
439	x	x			x	
38	x		x	x	x	x
39	x		x	x	x	x
144	x			x	x	x
264	x			x	x	x
414	x			x	x	x
145	x		x		x	
146	x		x		x	
187	x		x		x	

Plagioclase, forming a granoblastic mosaic, is usually bytownite, but labradorite is not unusual while andesine is rarely found. The felspars are often zoned, antiperthetic and have bent twinning lamellae. Occasionally plagioclase occurs as small porphyroblasts.

Orthopyroxene is most often present as small equidimensional crystals, euhedral to almost rounded in shape, and is usually distinctly to strongly pleochroic, but pale orthopyroxene does occur. Some of it diablastically encloses small grains of ore, hornblende and/or plagioclase and some of it is intergrown with clinopyroxene. It is often rimmed by fibrous alteration products with concomitant release of pellets of iron ore. Only in one specimen were schiller inclusions typically developed. In another specimen the orthopyroxene displayed preferred dimensional orientation which is at an angle to the direction imparted by biotite flakes in the same thin section.

Clinopyroxene is colourless to pale green and is usually poikiloblastic containing orthopyroxene, plagioclase, biotite and ore. Hornblende, present in some cases only as an accessory mineral, often forms well-developed subhedral prismatic poikiloblasts enclosing grains of quartz. The hornblende is of a brown to olive-green variety and in one of the sheared specimens, is being replaced by green hornblende together with the development of epidote and chlorite. Hornblende is usually evenly distributed, but in some specimens patches of fresh hornblende enclose and replace aggregates of altered orthopyroxene. When hornblende crystals are large, they disturb the granoblastic texture of the rock.

Biotite is of a foxy red colour and shows vague dimensional orientation. There can be no doubt that there are two generations of biotite in one of the specimens as the older short and stubby books of flakes arranged in one direction, show deformation in the form of kinking while the younger long and thin flakes lie with their longer dimensions in another direction not as distinctly developed as the older.

Quartz forms clear equidimensional grains, but as in the case of other rocks, lenticular aggregates of quartz are seen when the rocks are banded and the granoblastic texture destroyed. Iron ore minerals and apatite occur in all the rocks, usually as prominent accessory minerals, while zircon is not a common accessory. In only one of the many thin sections of granulites examined was green spinel found. Alteration products encountered include epidote, zoisite, chlorite and muscovite.

Two rocks containing olivine were found. At Bles Krantz (3018AD) a medium-grained black rock showing vague banding on the rough dark weathered surface occurs with the more usual granulites. In thin section it is seen to consist of coarse granoblastic, pale green faintly pleochroic hornblende forming the groundmass containing anhedral to subhedral colourless crystals of clinopyroxene, some orthopyroxene and olivine. In the Leliefontein Reserve near the southern boundary of sheet 3018AA, a coarse black rock showing strong dimensional orientation of the coarsely crystalline amphibole, was collected. This rock consists of a fresh mosaic of subhedral to euhedral crystals of brown hornblende with some altered olivine and hypersthene. Iron ore and apatite occur as accessory minerals. Olivine-bearing mafic rocks have also been found in the Keimoes area (von Backström, 1964).

Some of the pyroxene granulites contain potash felspar and these differ in certain respects from the types described above. The granulites containing potash felspar are usually more distinctly gneissose, their textures are nearly always heteroblastic and when granites have been emplaced in the vicinity, potash felspars appear as porphyroblasts. Although examples of the potash felspar-bearing granulites examined contain clinopyroxene, this mineral is usually absent from this group of rocks. The most common potash felspar found is untwinned, but microcline and microcline microperthite occur, while microperthite forms the porphyroblasts in two of the specimens collected. In these rocks quartz and plagioclase grains and crystals are larger than in the ordinary pyroxene granulites and the plagioclase if often antiperthitic while myrmekite is usually prominent.

The potash felspar-bearing granulites become topographically prominent when felspar-quartz augen develop in them and when they form large bands, they have been distinguished on the map as hornblende-hypersthene gneisses. Although these gneisses resemble the Nababeep gneiss, they are always darker and weather to a darker brown colour and south of Elandspoort beacon (3018AB), they are traversed by wide leucocratic neosomes. Other distinguishing features are the large number of fine-grained mafic skialiths in them and also local concentrations of much magnetite.

Cordierite was found in a few of the pyroxene granulites examined and in these specimens the mineral resembles felspar and never displays any of its characteristic features such as twinning, pleochroic haloes or distinctive alteration.

Table 8. The mineral assemblages of some of the potash felspar-bearing pyroxene granulites

Specimen No.	Orthopyroxene	Amphibole	Biotite	Plagioclase	K-felspar	Quartz	Chlorite
640	x	x	x	x	x	x	x
94	x	x	x	x	x	x	
191	x	x	x	x	x	x	
326	x	x	x	x	x	x	
411	x	x	x	x	x	x	
632	x	x	x	x	x	x	
211	x		x	x	x	x	x
130	x	x	x	x	x		
177	x		x	x	x	x	
194	x		x	x	x	x	
225	x		x	x	x	x	
228	x		x	x	x	x	
281	x		x	x	x		
400	x			x	x	x	

East of O'okiep a basic rock, described as a metamorphosed diabase sill, occurs within the gneisses (Cornelissen, 1958). It is described as occurring interbedded with the paragneisses in a definite stratigraphic position. The pyroxene granulites which are so widespread in the eastern part of the area mapped, are singularly absent in the O'okiep area and it is thought that this particular "sill" is in fact the local representative of the granulites. Prof. M. Mathias has kindly made available for this report modes of this "sill" calculated by her.

Table 9. Modal compositions of the pyroxene granulites

Specimen No.	Plagioclase	K-felspar	Orthopyroxene	Clinopyroxene	Hornblende	Biotite	Quartz	Ore	Apatite
1	39.3		26.9	2.6	26.9	1.3		3.0	
2	40.2		30.9	1.6	23.2	0.9		3.2	
3.	44.3		34.4	11.3	1.0	4.0	1.9	3.1	
4	45.7		26.4	18.9	0.1	2.9	0.4	5.6	
5	38.8		41.1	1.9	12.2	2.5		3.5	
6	86.7		12.2	0.2	0.2	0.1		0.6	
7	40.9		31.8	6.5	14.1	3.8		2.9	
9	67.2	11.3	9.8				7.0	3.9	0.8
10	42.3	2.5	13.9	6.7	24.8	0.4	3.6	5.3	0.5
11	39.3	1.2	2.9	4.1	39.5	6.1		6.2	0.7
12	36.4	5.9	16.4	14.4	5.6	0.1	8.0	12.6	0.6
13	46.3		24.1	19.0	0.4		1.2	8.5	0.5
14	38.4	8.2	14.8	18.9	1.3		6.9	11.0	0.5
15	37.9		28.8	15.1	0.9	11.1		5.9	0.3
17	29.0	20.2		7.8	16.3		20.7	6.0	
18	47.4	6.2				5.2	37.1	3.0	1.1
19	46.7	5.4	29.0	7.7			4.7	5.6	0.9
20	44.4		20.6	17.2		9.4		7.2	1.2
21	38.3	3.6	11.6	23.2	6.9	8.3	0.2	7.4	0.5
22	29.0	12.5	11.2	10.2		1.0	25.5	9.4	1.2
23	39.1		9.3		26.8	2.8	17.7	3.5	0.8
24	34.8		21.5	16.9	2.2	20.8		3.8	

To the north of Soetwater (2917AB), the mafic rocks can be directly related to metavolcanics. In that area, where the grade of metamorphism is lower, some of the mafic rocks still show structures which can only be described as scoriaceous. On top of the hills to the north of this occurrence and north of the present area, metamorphosed lavas in which volcanic structures can still be recognised, have tentatively been correlated with the Wilgenhoutdrift "Series" (De Villiers and Söhnge, 1959).

(ii) Garnet granulites

Garnet granulites are found as small lenses, in some cases boudins, within the pyroxene granulites or occasionally as lenticular bodies in the Nababeep gneiss. All the specimens have been collected in an area south and south-east of Springbok (2918CC, 2917DD and 3018AA). The most westerly occurrence is on the farm Namaras and the most southerly occurrence on Anegas (3018AA).

These rocks are usually fine grained, dark grey and one specimen has a spotted appearance with elongate aggregates of dark minerals in a leucocratic matrix. In thin section the texture is seen to be granoblastic and the rocks consist of a matrix of bytownite and quartz with clinopyroxene, often in clusters and nearly always mantled by distinctively coloured orange-pink garnet. (Fig. 3). Bent twinning lamellae of plagioclase is seen in nearly all the specimens examined and the clinopyroxene is distinctly pleochroic from yellow to blue green. Acicular ore inclusions in parallel arrangement occur in the clinpyroxene of one of the specimens and Prof. M. Mathias determined the pyroxene of one of the garnet granulites as having $2V \pm 76^{\circ}$ and identified it as aegerine. However, most of these pyroxenes are optically positive and therefore probably aegerine-augite.

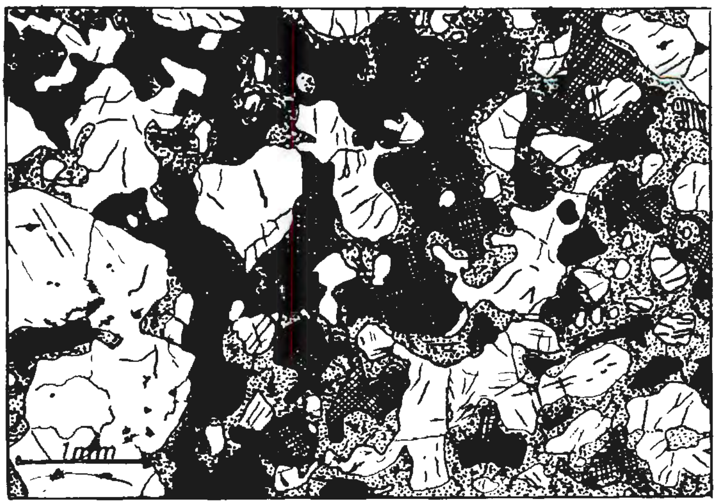

Fig. 3. Garnet granulite consisting of clinopyroxene (hatched) rimmed by garnet (stippled) and plagioclase

Garnet is poikiloblastic, containing fairly large grains of quartz with which it may be intergrown. Sphene as large anhedra is always a prominent constituent of the garnet granulites and is occasionally found mantling the clinopyroxene in the place of garnet. Zircon and apatite are sparsely present as accessory minerals.

One specimen collected on Drooge Daap probably belongs to this group by virtue of its texture, the distinctive colour of the garnet and the same mineral assemblage but for the absence of pyroxene.

4. Calcareous rocks

Thin bands and small bodies of crystalline limestone occurring within the paragneisses have been recorded by Poldervaart and von Backström (1949, p.436) in the Keimoes area, by Brink (1950, p.111) north-east of Bitterfontein and in a few localities in the Richtersveld (De Villiers and Söhnge, 1959) while De Jager and Simpson (1962) described the wollastonite occurrences near Garies.

Apart from the limestone mentioned by Brink, several small occurrences of crystalline dolomitic limestones were encountered during the present survey. Near the base of the mafic rocks and in the ultramafic belt from Dikmatje (3018AB) along the northern flank of the hills stretching to the west to north of Rooifontein and also at Rooifontein, several bands of these rocks are to be found. Associated small lenses of metaquartzite are found in places. Only the occurrence at Onder-Gamoep (2918CD) could be shown on the map as the others mentioned above, as well as that found at Anegas (3018AA), are too small to indicate. Many similar bodies of crystalline limestones could conceivably occur elsewhere in the area as they are easily missed unless they happen to be on a line traversed.

The crystalline limestones are usually fine grained, light grey in colour, often with small pale green to yellowish spots. In thin section the even-grained mosaic of calcite (dolomite?) is seen to contain spherules of antigorite, occasional flakes of phlogopite and nearly always a few grains of bright green spinel. At Dikmatje the rocks have asbestiform bands which, under the microscope, are seen as fibres of chrysotile lying across the lenticular bands it forms. The calcite is frequently biaxial with a small optic axial angle and the crystals have dense borders due to numerous small inclusions. The clear recrystallised cores of the calcite crystals are usually twinned and often show uneven extinction. The specimen from Anegas is different in having a brown colour with irregular pale patches and in being coarsely crystalline. The brown colour is due to dense patches of granules of iron ore. This rock also contains a little brucite.

One limestone picked up as float, was found south of Rietfontein (2918CC) and although a search was made in the vicinity, an outcrop of this rock could not be found. It is possible that this limestone does not belong to the paragneisses of Namaqualand. The limestone is a finely crystalline grey to buff rock with typical limestone weathering and it has thin anastomosing chert bands. It consists of dense crystals of calcite in a fine calcareous matrix with some irregular chalcedonic veins and aggregates of fine granules of iron ore. The calcite crystals show elongation across the ribbons between the siliceous veinlets.

Two types of pyroxene-bearing rocks are found in association with the crystalline limestones from which they almost certainly have been derived. One is a coarse-grained, pale green, friable rock consisting of an equigranular mosaic of colourless diopside while the other is a fine-grained black rock composed of the same mineral, but in addition also contains patches of calcite, some apatite and a few grains of spinel. A similar specimen was found to contain some phlogopite.

The wollastonite occurs in the Leliefontein Reserve and also west of Roode Berg Kloof (3018AC) where this mineral, forming the bulk of the rock with crystals up to 6 cm across, occurs with calcite, diopside and garnet. In one of the thin sections examined the wollastonite is poikiloblastic with small inclusions of all the other minerals present in the rock. De Jager and Simpson (1962, p.132) also record the presence of vesuvianite and plagioclase in the wollastonite-bearing rocks, but these minerals were not seen in these rocks collected during this survey.

5. Migmatitic rocks

Many of the rock types described above are migmatitic in the sense that they are banded with alternating dark and leucocratic layers as defined by Holmes (1920). In many localities in the eastern part of the area mixed rocks which can only be described as migmatites have developed locally and on the maps these rocks have been included with the rocks from which they evolved. However, the types described below have been mapped as lithological entities and are representatives of advanced migmatisation.

(a) Porphyroblastic gneisses

Several types of porphyroblastic gneisses are found in Namaqualand, but those most distinctive occur commonly in areas where bosses and sheets of granite attain their widest distribution. In the present area they are of wide-spread occurrence in the south and again appear along the Mara River (2917CB) and in the northernmost parts. Similar rocks are described and microscopic descriptions given by De Villiers and Söhnge (1959, p.109) for the Richtersveld, by Jansen (1960, p.31-32) and by Pike (1959, p.29-30) for the region to the south of the present area. Brink (1950, p.154) included the porphyroblastic gneisses with what he terms "Namaqualand Granite". De Villiers and Söhnge stated that the porphyroblastic gneiss fairly certainly resulted from the felspathisation of the biotite gneiss and suggest that the change possibly occurred at the time of the intrusion of the Richtersveld granite. Jansen recorded that the composition of the porphyroblastic rocks depends largely on that of the original gneissic or metamorphic rock now altered, while Pike listed the reasons why the porphyritic granite-gneiss is not of truly migmatic origin. From the field evidence in the present area, it is clear that the conclusions reached by the above-mentioned investigators are correct and that the porphyroblastic gneisses were essentially derived from the fine-grained biotite gneisses described above. The more mafic rocks were also affected by the same process, but to a lesser extent.

The porphyroblastic gneisses are grey to brownish grey rocks, coarse grained and usually without any vestige of banding or directional structure and their felspar porphyroblasts, which are up to 10 cm in length, are of haphazard orientation. These rocks have the same mineralogical composition as the fine-grained biotite gneisses, but for the porphyroblasts of perthite or microcline microperthite. The strong alignment of flakes of biotite in the biotite gneisses is not nearly as pronounced or, more usually, completely absent in the porphyroblastic rocks. Because of the fairly large percentage of plagioclase, in some rocks comprising more than a third of the total volume, these gneisses are usually granodiorite in composition.

In places these gneisses have intrusive relationships with the paragneisses and the best examples of such circumstances occur on the farm Bitterfontein (3018CC) where roof pendants of quartzites and leptites have been found. Pike (op. cit., p.25) cited a similar situation in the area to the south-east where the metaquartzite becomes garnetiferous.

Some of the rocks were found to contain hornblende and one specimen from the porphyroblastic gneiss about 10 km north-west of Remhoogte (3018AD) contains hypersthene and is an example of the hornblende-hypersthene gneisses described later.

The way in which the porphyroblastic rocks form is very obvious in the Nuttabooi area and along the Mara River (2917CB). The biotite gneisses and pyroxene granulites have been intruded by pegmatites and thin sheets of granite. The porphyroblasts develop in the mafic rocks and they become coarse grained and resemble dark granites containing skialiths of unaltered mafic rocks, the whole assemblage displaying a streaky appearance with rocks ranging in colour from coarse leucocratic to fine grained and mafic (Plate III).

Plate II. Aerial view of hills to the south of Eendoorn from the west. The paragneisses (dark) overlying Nababeep gneiss (exfoliation domes). Note the shearing of the gneisses parallel to the contact

In some places wide irregular leucocratic dykes traverse the porphyroblastic gneisses. These dykes are most prominent in the area east of Doornkraal (3018CA) and are conspicuous even at a distance as white bands in the dark gneisses. On closer examination these dykes are seen to be composed of medium and even-grained rocks with evenly-distributed grains of dark quartz in a white felspathic matrix. The rocks consist of the same minerals as the alaskitic granites; microcline microperthite, perthite, quartz and densely altered plagioclase with very minor amounts of biotite, ore and zircon and are similar in composition and occurrence to those described by De Villiers and Söhnge (1959).

Plate III. Growth of felspar porphyroblasts forming streaks in the mafic rocks along the Mara River

(b) Migmatites

Truly mixed rocks occur over a wide area in an east-west zone parallel to and straddling latitude 30°30'S. These fairly leucocratic gneisses are irregularly banded and contain many small to large fine-grained mafic and quartzo-felspathic skialiths, stringers and irregular or disjointed streaks. The coarseness of the gneisses is very variable from fine-grained banded to finely lined to coarsely crystalline, almost granitic, and it was found impossible to map all the variations in greater detail in the reconnaissance style of the map.

The foliation is generally wavy and mafic bands are often dissipated into strings of large garnet insets in the more granitic types of migmatite. Finely banded or lined biotite gneiss develop augen and then form topographically more prominent outcrops. In places many small evenly-distributed felspar porphyroblasts form in the mafic rocks which then have gradational contacts with the leucocratic hosts. In the south of the area two smaller occurrences of similar rocks were seen on Modderfontein and Tafelberg (3018CD), but there the rocks could be separated into mafic and granitic counterparts on the map. As can be expected, the mineral compositions of the rocks collected amongst the migmatites can be matched by almost all the other types described under the metavolcanics and paragneisses as well as the granitic gneisses to follow.

6. Intrusive rocks

(a) Granitic rocks

(i) Porphyroblastic granite-gneiss

In widely separated areas coarsely porphyroblastic granite-gneisses have been mapped in the present area. The most southerly occurrence lies along an east-west belt from Eselsfontein to Paulskraal (3018AC) where these rocks show intrusive relationships with the paragneisses and have been deformed with them. Farther north the granite-gneiss lies within the confines of a major synform from Dansekraal (2917DC) and reaching east along the northern edges of sheets 2917DD and 2918CC and again farther west to the north-east of Komaggas. The northerly occurrences may prove to be a variation of the Nababeep gneiss as the porphyroblastic gneisses there appear to overlie the normal stratigraphic sequence conformably in this inverted succession, but because of the remarkable similarity with the southern types, they have been grouped together.

Similar rocks, which also share intrusive relationships with the paragneisses, form an outcrop 6.5 km west of Platbakkies (3018AD) too small to appear on the map, but these rocks underlie a wide area to the east of Banke (3018AD) outside the confines of the present area.

The porphyroblastic granite-gneisses are coarsely crystalline with large white, poorly defined felspar porphyroblasts separated from one another by thin irregular lines of dark minerals imparting a rude foliation to the rock. There is a variation in the amount of dark minerals present, but the rocks are always more melanocratic and more coarsely crystalline than the Nababeep gneiss. In places the gneiss has a tendency to become granitoid consisting almost completely of porphyroblasts and then there are swarms of fine-grained quartzo-felspathic bands traversing the rocks. At its contacts the gneiss becomes more leucocratic and the augen elongated.

These gneisses also contain numerous fine-grained mafic skialiths which merge with the enclosing gneiss, and clusters and patches of fairly coarse garnets are of frequent occurrence. The elongated skialiths and garnet clusters lie with their longer dimensions parallel to the rude foliation in the rock.

In the Eselsfontein area the granitic gneisses display intrusive contacts which are oblique to the strike of foliation in the invaded rocks. The porphyroblasts are from 6 to 8 cm long and almost 2 cm across and are dimensionally orientated parallel to the regional foliation, but at an angle to the contacts while the leucocratic bands tend to be parallel to the contacts. Some of the coarser leucoveins have been found to parallel the north-south direction of faulting across the regional foliation and at Paulskraal (3018AC) the mafic skialiths lie with their longer dimensions at an angle to the strike of the foliation there.

North-east of Komaggas the porphyroblastic gneisses are coarsely migmatitic in having wide conformable leucocratic banding (Plate IV). The migmatitic banding has been folded since its formation and is older than the Concordia-type granite described below. Farther east at Dansekraal (2917DC) the leptites have not been completely incorporated by the granitic gneisses. The same seems to have happened to the west of Platbakkies (3018AD) where leucocratic lines of boulders lie on the outcrops of the gneisses there.

Plate IV. Coarse migmatitic banding in the porphyroblastic gneisses at Biesies

The most prominent mineral of the porphyroblastic granite-gneisses is quartz which forms large anhedra showing undulose extinction and is surrounded by microcline, microcline microperthite, oligoclase and aggregates of dark minerals consisting of clinopyroxene, hornblende, ore, apatite and rutile. Myrmekite is prominent, in some cases altered to greenish masses of chlorite and sericite. The porphyroblasts are poikiloblasts of perthite, rarely microcline, and some show pronounced uneven extinction. Biotite is usually of a brown variety, but is often greenish due to alteration and occurs in clusters with ore. Hornblende and augite were only found in thin sections of the Eselsfontein occurrence, but Mr. B. Packham from O'okiep states that hypersthene has been found in the porphyroblastic gneisses south of Springbok.

(ii) Streaky augen gneisses

A distinctive streaky augen gneiss occurs in the southern part of the area (sheets 3018CA and CC). This rock is streaky, poorly banded and fairly coarse with subhedral porphyroblasts in some localities and occurs at the base of the paragneisses in the south-west, but farther east it is interlayered with the metasediments. At Dikdoorn (3018CA) however, rafts of paragneisses occur in these augen gneisses which apparently were originally emplaced as an intrusive and was deformed, together with the paragneisses, since the earliest episodes of folding and metamorphism.

To the south at Bruintjes Hoogte (3018CC) the streaky gneisses have been folded into the shape of an extensive synform, but it is clear from the present disposition of these rocks that they have been involved in a phase of deformation earlier than that responsible for the formation of the synform.

In thin section the texture is seen to be heteroblastic, consisting of large plates of microcline microperthite or poikiloblasts of perthite with quartz, oligoclase, which is often much altered, myrmekite, brown biotite, often much chloritised or completely altered to ragged flakes of chlorite, ore, zircon and apatite. Alteration of the felspar yields chlorite, epidote, and in one specimen examined, calcite. The garnet occurs sparsely as small diablasts containing quartz, biotite and ore and is seen to predate the shearing to the south of Uitspanberg (3018CD) where this mineral shows peripheral fibrous alteration. There appears to be two generations of biotite in some of these rocks, the biotite of the second generation being fresh and also forming coronas of fine flakes around the grains of ore.

(iii) Concordia gneissic granites

The name Concordia granite has been coined by the geologists of the O'okiep copper district for a belt of granitic gneisses which stretches east-west across the country north of Nababeep and O'okiep. It is proposed to extend the name to include all similar gneissic granites of late-tectonic age.

Gevers et al. (1937, p.33) named an acid aplitic granite the "Een Riet type" to distinguish it from the darker gneissose varieties. Later he (Gevers, 1940, p.ixix-lxx) drew attention to the fact that the rock that Mathias (1940, p.193-195) described as the Aggenys Granite is the same as his Een Riet type and judging by the modes, these rocks are the same as those now referred to as the Concordia granite. Strauss (1941, p.39-40) gave a good description of the granite and enumerated the constituent minerals, but appears to have confused it with the quartzo-felspathic rocks forming part of the paragneiss sequence. Brink (1950) incorporated many of the paragneisses in his descriptions of the "granites" and his fine-grained granites which contain few mafic minerals (op. cit., p.152) are without doubt the granites described here. Jansen (1960) and Pike (1959) found similar granites to the south of the present area, while to the north-east these granites are described as aplogranites by Coetzee (1941, p.181-182). Two chemical analyses and the calculated norms are given by Coetzee (op. cit., p.189-191) and he concluded that the aplogranites are the acid differentiates of the granite-gneiss. Mathias (1940, p.199-201) also believed that the Aggenys Granite is an acid marginal phase of the Namaqualand granite-gneiss having the composition of a normal alkali-granite and together with the granite-gneiss is correlated with the Cape Granites. It is this correlation which is questioned by Gevers (1940, p.lxx) for several reasons, the most important being that these granites are older than the Nama System, while the Cape Granites intrude rocks of the Malmesbury "System". He also mentioned (p.lxxviii) the presence of a younger, less biotitic granite, lighter in colour and often reddish yellow on weathered outcrops, as occurring east of the Kamiesberg and west of Kaauwgoedvlakte. He also recorded the considerable variations within the granite, some types being markedly porphyritic, and that these rocks are widely distributed from there to east of Springbok. The present survey has confirmed all Gevers' ideas about these so-called "younger" granites as well as the occurrence of granites even younger in age along the coast.

In the present area the Concordia granitic gneiss is of widespread occurrence, mostly as thin, almost conformable sheets throughout the area mapped, but forms large bodies especially on sheet 3018AB between Vaalputs, Riembreek to Kap Kap and Remhoogte on sheet 3018CB as well as a number of scattered localities in the southernmost part of the area. It is again prominent to the north-west of Komaggas and farther north towards Langhoogte (2917CB) and again in the most northerly parts of the area now mapped.

The distribution of the Concordia granite is irregular, but generally it forms dyke and sheet-like bodies emplaced along the foliation planes of the host rocks. In the area west of

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In widely separated areas coarsely porphyroblastic granite-gneisses have been mapped in the present area. The most southerly occurrence lies along an east-west belt from Eselsfontein to Paulskraal (3018AC) where these rocks show intrusive relationships with the paragneisses and have been deformed with them. Farther north the granite-gneiss lies within the confines of a major synform from Dansekraal (2917DC) and reaching east along the northern edges of sheets 2917DD and 2918CC and again farther west to the north-east of Komaggas. The northerly occurrences may prove to be a variation of the Nababeep gneiss as the porphyroblastic gneisses there appear to overlie the normal stratigraphic sequence conformably in this inverted succession, but because of the remarkable similarity with the southern types, they have been grouped together.

Similar rocks, which also share intrusive relationships with the paragneisses, form an outcrop 6.5 km west of Platbakkies (3018AD) too small to appear on the map, but these rocks underlie a wide area to the east of Banke (3018AD) outside the confines of the present area.

The porphyroblastic granite-gneisses are coarsely crystalline with large white, poorly defined felspar porphyroblasts separated from one another by thin irregular lines of dark minerals imparting a rude foliation to the rock. There is a variation in the amount of dark minerals present, but the rocks are always more melanocratic and more coarsely crystalline than the Nababeep gneiss. In places the gneiss has a tendency to become granitoid consisting almost completely of porphyroblasts and then there are swarms of fine-grained quartzo-felspathic bands traversing the rocks. At its contacts the gneiss becomes more leucocratic and the augen elongated.

These gneisses also contain numerous fine-grained mafic skialiths which merge with the enclosing gneiss, and clusters and patches of fairly coarse garnets are of frequent occurrence. The elongated skialiths and garnet clusters lie with their longer dimensions parallel to the rude foliation in the rock.

In the Eselsfontein area the granitic gneisses display intrusive contacts which are oblique to the strike of foliation in the invaded rocks. The porphyroblasts are from 6 to 8 cm long and almost 2 cm across and are dimensionally orientated parallel to the regional foliation, but at an angle to the contacts while the leucocratic bands tend to be parallel to the contacts. Some of the coarser leucoveins have been found to parallel the north-south direction of faulting across the regional foliation and at Paulskraal (3018AC) the mafic skialiths lie with their longer dimensions at an angle to the strike of the foliation there.

North-east of Komaggas the porphyroblastic gneisses are coarsely migmatitic in having wide conformable leucocratic banding (Plate IV). The migmatitic banding has been folded since its formation and is older than the Concordia-type granite described below. Farther east at Dansekraal (2917DC) the leptites have not been completely incorporated by the granitic gneisses. The same seems to have happened to the west of Platbakkies (3018AD) where leucocratic lines of boulders lie on the outcrops of the gneisses there.

Plate IV. Coarse migmatitic banding in the porphyroblastic gneisses at Biesies

The most prominent mineral of the porphyroblastic granite-gneisses is quartz which forms large anhedra showing undulose extinction and is surrounded by microcline, microcline microperthite, oligoclase and aggregates of dark minerals consisting of clinopyroxene, hornblende, ore, apatite and rutile. Myrmekite is prominent, in some cases altered to greenish masses of chlorite and sericite. The porphyroblasts are poikiloblasts of perthite, rarely microcline, and some show pronounced uneven extinction. Biotite is usually of a brown variety, but is often greenish due to alteration and occurs in clusters with ore. Hornblende and augite were only found in thin sections of the Eselsfontein occurrence, but Mr. B. Packham from O'okiep states that hypersthene has been found in the porphyroblastic gneisses south of Springbok.

(ii) Streaky augen gneisses

A distinctive streaky augen gneiss occurs in the southern part of the area (sheets 3018CA and CC). This rock is streaky, poorly banded and fairly coarse with subhedral porphyroblasts in some localities and occurs at the base of the paragneisses in the south-west, but farther east it is interlayered with the metasediments. At Dikdoorn (3018CA) however, rafts of paragneisses occur in these augen gneisses which apparently were originally emplaced as an intrusive and was deformed, together with the paragneisses, since the earliest episodes of folding and metamorphism.

To the south at Bruintjes Hoogte (3018CC) the streaky gneisses have been folded into the shape of an extensive synform, but it is clear from the present disposition of these rocks that they have been involved in a phase of deformation earlier than that responsible for the formation of the synform.

In thin section the texture is seen to be heteroblastic, consisting of large plates of microcline microperthite or poikiloblasts of perthite with quartz, oligoclase, which is often much altered, myrmekite, brown biotite, often much chloritised or completely altered to ragged flakes of chlorite, ore, zircon and apatite. Alteration of the felspar yields chlorite, epidote, and in one specimen examined, calcite. The garnet occurs sparsely as small diablasts containing quartz, biotite and ore and is seen to predate the shearing to the south of Uitspanberg (3018CD) where this mineral shows peripheral fibrous alteration. There appears to be two generations of biotite in some of these rocks, the biotite of the second generation being fresh and also forming coronas of fine flakes around the grains of ore.

(iii) Concordia gneissic granites

The name Concordia granite has been coined by the geologists of the O'okiep copper district for a belt of granitic gneisses which stretches east-west across the country north of Nababeep and O'okiep. It is proposed to extend the name to include all similar gneissic granites of late-tectonic age.

Gevers et al. (1937, p.33) named an acid aplitic granite the "Een Riet type" to distinguish it from the darker gneissose varieties. Later he (Gevers, 1940, p.ixix-lxx) drew attention to the fact that the rock that Mathias (1940, p.193-195) described as the Aggenys Granite is the same as his Een Riet type and judging by the modes, these rocks are the same as those now referred to as the Concordia granite. Strauss (1941, p.39-40) gave a good description of the granite and enumerated the constituent minerals, but appears to have confused it with the quartzo-felspathic rocks forming part of the paragneiss sequence. Brink (1950) incorporated many of the paragneisses in his descriptions of the "granites" and his fine-grained granites which contain few mafic minerals (op. cit., p.152) are without doubt the granites described here. Jansen (1960) and Pike (1959) found similar granites to the south of the present area, while to the north-east these granites are described as aplogranites by Coetzee (1941, p.181-182). Two chemical analyses and the calculated norms are given by Coetzee (op. cit., p.189-191) and he concluded that the aplogranites are the acid differentiates of the granite-gneiss. Mathias (1940, p.199-201) also believed that the Aggenys Granite is an acid marginal phase of the Namaqualand granite-gneiss having the composition of a normal alkali-granite and together with the granite-gneiss is correlated with the Cape Granites. It is this correlation which is questioned by Gevers (1940, p.lxx) for several reasons, the most important being that these granites are older than the Nama System, while the Cape Granites intrude rocks of the Malmesbury "System". He also mentioned (p.lxxviii) the presence of a younger, less biotitic granite, lighter in colour and often reddish yellow on weathered outcrops, as occurring east of the Kamiesberg and west of Kaauwgoedvlakte. He also recorded the considerable variations within the granite, some types being markedly porphyritic, and that these rocks are widely distributed from there to east of Springbok. The present survey has confirmed all Gevers' ideas about these so-called "younger" granites as well as the occurrence of granites even younger in age along the coast.

In the present area the Concordia granitic gneiss is of widespread occurrence, mostly as thin, almost conformable sheets throughout the area mapped, but forms large bodies especially on sheet 3018AB between Vaalputs, Riembreek to Kap Kap and Remhoogte on sheet 3018CB as well as a number of scattered localities in the southernmost part of the area. It is again prominent to the north-west of Komaggas and farther north towards Langhoogte (2917CB) and again in the most northerly parts of the area now mapped.

The distribution of the Concordia granite is irregular, but generally it forms dyke and sheet-like bodies emplaced along the foliation planes of the host rocks. In the area west of

Bokputs (3018AB) large granite sheets occur between the sheared rocks there and the granitic assemblage has been emplaced in the form of a multiple phacolith resulting in the growth of large, very coarse pegmatitic nodules in the sheared rocks at Riembreek and Kap Kap (3018AB). In many areas numerous small bosses of granite occur intruded into the paragneisses, notably south of Couragie Fontein (3018AB) and in the vicinity of Remhoogte (3018AB).

Along the course of the Buffels River on the farm Sannagas (2917DC) pods forming along granitic leucosomes are accommodated in mild folds which formed at the time of emplacement of the granite. Pegmatitic phases of the granite were intruded in lit-par-lit fashion along the existing migmatitic banding in the gneisses there and result in peculiar pinch-and-swell structures. These bodies are rounded or elongated, all with irregular boundaries, emplaced like beads on a string which coincides with the banding in the host rocks. The pegmatitic knots did not cause any deviation in the foliation or banding as in the case of larger Concordia granite intrusions. Farther west of this locality, coarse concentrations of dark constituents rim the edges of granitic bodies.

Where the Concordia granite is intruded into the Nababeep gneiss, the contact zone is an area of many tongues of granite reaching into the gneiss while the granite includes lenses of the gneiss. The contact zone is often marked by aplitic and pegmatitic phases which tend to be emplaced along the foliation planes of the host rocks. The results of intrusion of granite into mafic rocks have been described above and it would suffice here to mention that the mafic rocks lie as lenticular bands and stringers in the granite and they taper into the granite as diminishing clusters of garnets. The emplacement of granite in the proximity of the mafic rocks also resulted in the growth of porphyroblasts in the paragneisses. The effects along the Buffels River at Bontekoe (2917CB) first resulted in the destruction of banding due to the growth of coarse hornblende crystals (Plate V) and in the development of stictolithic (fleck) structure (Mehnert, 1968, p.37-39). Incorporated mafic lenses are undisturbed and retain the same directions of planar and linear structures as the host rocks. This feature as well as the fact that thermal contact phenomena are never seen indicate that the granites were not forcibly injected and that the temperature of the invaded rocks must have been as high or almost as high as that of the invading granites.

Quartzo-felspathic rocks become coarser grained in the vicinity of the Concordia granites and tend to lose their banded nature. In other places the leptites become hard and appear more quartzitic and then the banding is more distinctly noticeable on the weathered surfaces which become more reddish in colour.

Plate V. Destruction of the fine banding in mafic rocks in the proximity of granite, Bontekoe. Irregular leucocratic bands with clusters of coarse dark minerals form. The fracture at the tip of the pick is due north-south

The Concordia granitic gneiss is a white to pinkish rock which, when the intrusive bodies attain a fair size, crops out as large smooth boulders which can be recognised even at a distance. As Gevers (1940) records, there is a considerable variation within the granites and when they are finer grained, they are indistinguishable from leptynites and pink gneisses and present difficulties of recognition, also encountered by previous investigators. The porphyritic varieties of the granites are much like the younger granites in the western part of the area and it is perhaps fortunate that the coarsely crystalline varieties do not appear to occur west of the escarpment.

The finer grained phases of the granite frequently show lineations expressed either in the elongation of quartz grains or in the arrangement of felspar plates which were found to parallel xenoliths of the invaded rocks in some localities. When the granites are sheared they become cleaved and flaggy outcrops mark the paths of shear zones. De Villiers and Söhnge (1959, p.109) described muscovitised granites occurring in the Richtersveld. From the petrographic description these are similar to highly sheared gneisses occurring in the Vredefontein (2917AA) area, and farther east towards Hardevlakte. There can be little doubt that these muscovitised granites can be correlated with the Concordia type granite and have been sheared before, during and after the deposition of the sediments of the Stinkfontein Formation. These rocks become increasingly more sheared on proceeding west as the rocks of the Stinkfontein Formation are approached.

The modes of these granitic rocks have been given by Strauss (1941, p.40), Mathias (1940, p.194) and Coetzee (1941, p.182) and the minerals listed are quartz, potash felspar, plagioclase as the essential minerals with biotite, muscovite, ore, apatite, zircon and sphene. During the survey more than 30 specimens were collected over a very wide area and in addition to the abovementioned minerals, minor amounts of hornblende were found in three of the rocks and in the hybridised types, diablastic grains of garnet and flakes of fresh red-brown biotite also become prominent. The plagioclase content varies considerably from scarce to obvious and this mineral is always much altered, while myrmekite is frequently encountered. Biotite is frequently chloritised and in some sheared specimens the biotite flakes are bent and a second generation of fresh brown biotite is observed. In these rocks quartz is cracked or occurs as lenticles with the longer dimensions parallel to the direction of the shear.

Small isolated leucocratic bodies which appear different from the ordinary granitic gneiss in having a fine granulose texture, have been found in some localities south of latitude 30°30'S, but under the microscope they are seen to have exactly the same mineral assemblage as the Concordia granitic gneiss. They appear thus to belong to this group of rocks and their fine-grained character can possibly be ascribed to the small size of the intrusives.

(iv) Younger granites

De Villiers and Söhnge (1959, p.85) correlated a small occurrence of granite which they named "Kromnek granite" in the southeastern part of their area with the Richtersveld Igneous Complex. Several similar granites were found in the western part of the area now mapped. Jansen (1960, p.50-52) described the granite plutons occurring in the Bitterfontein area and one, which he named the "De Toren Pluton" also crops out in the south-westerly corner of the present area. In the Bitterfontein area the contacts between the granite and the gneisses are exposed, but north of latitude 31°00'S, the southern boundary of the present map, the contact between the gneisses and the granite occurs along the line of a fault. North-northwesterly striking faults also traverse the granite. As Jansen described, the granite is entirely devoid of xenoliths and the only signs of metamorphism which could possibly be ascribed to the granite in the present area are the occurrence of a coarsely spotted rock occurring at the eastern boundary of the granite. These spots have been found to consist of decussate aggregates of chlorite.

The granite is a leucocratic, medium to coarse-grained rock with evenly distributed dark minerals. The texture is xenomorphic and the rock consists of orthoclase, microperthite, quartz and oligoclase with ragged flakes of biotite occurring in clusters as well as a little apatite, zircon and ore. Jansen (op. cit., p.51) gave an analysis of the De Toren Pluton granite and also listed hornblende as occurring in the granite, but this mineral was not seen in the thin sections of specimens collected during the present survey. According to Jansen the granite grades into a granodiorite, whereas its border-facies is more acid and leucocratic. The correlation of the De Toren Pluton must at this stage remain uncertain as it can perhaps be of the age of either the Kuboos granite or the Richtersveld Igneous Complex. These are dated as 550±20 My and 850±20 My respectively (De Villiers and Burger, 1967). It is perhaps of interest to mention that Haughton (1969, p.254-255) tentatively correlated the syenites of the Bitterfontein area, named the Klein Kogelfontein Complex by Jansen, with the Richtersveld Igneous Complex.

The north-westerly occurrences of granite appear to be different from the Concordia granite in being coarser grained and in forming discrete bodies which were not influenced by the existing foliation when they were emplaced. Furthermore, they postdate the banding and formation of porphyroblasts in the host rocks and also differ from the Concordia granite in having a greater percentage of dark constituents and in a total lack of directional elements. De Villiers and Burger (1967) suggested that the Richtersveld granite may represent a late event in the genesis of the "Namaqualand Granite-gneiss Massif".

The largest body of these granites was found at Steenbok (2917AD) while some smaller satellite bodies are found towards the west. A smaller body occurs at Haouseep (2917AB) and a small dyke-like body of granite occurs west of the Tussenin hills (2917AB). Farther east a brown-weathering coarse rock forms a prominent lenticular outcrop on which Chabiesies beacon (2917AB) is sited, but this rock shows some features reminiscent of the Concordia granite and may possibly be of the earlier group of granites.

The younger granites are usually medium grained, grey and have an even distribution of dark constituents. They weather to a light or dark brown surface and some of the rocks have pink felspars. The dyke-like body west of Tussenin beacon is fine grained at the contact, but in the centre of the body large porphyritic felspar crystals up to eight cm in length are found. The rocks consist of microcline, microcline-microperthite, microperthite, quartz, altered plagioclase, biotite, ore, apatite, zircon and sphene. Alteration products noticed include muscovite, chlorite, epidote and calcite. These rocks thus have the same mineralogical composition as the Concordia granite, but they contain a greater proportion of biotite. The granite at Haouseep contains some hornblende in addition to the above-mentioned minerals, while a little fluorite was found in the granite from Steenbok.

Peculiarly disturbed folded rocks occur in a zone from west of Dikgat (2917CA) again seen at Meidjes Karroo (2917AC), on the road between Port Nolloth and Steinkopf south of Hootjes Vlei (2917AB), at Haouseep and in the Tussenin Hills (Plate VI). In these places the usual regular pattern has been plastically deformed and the structural elements of the folds, although still easily recognised, do not adhere to the directions deciphered elsewhere.

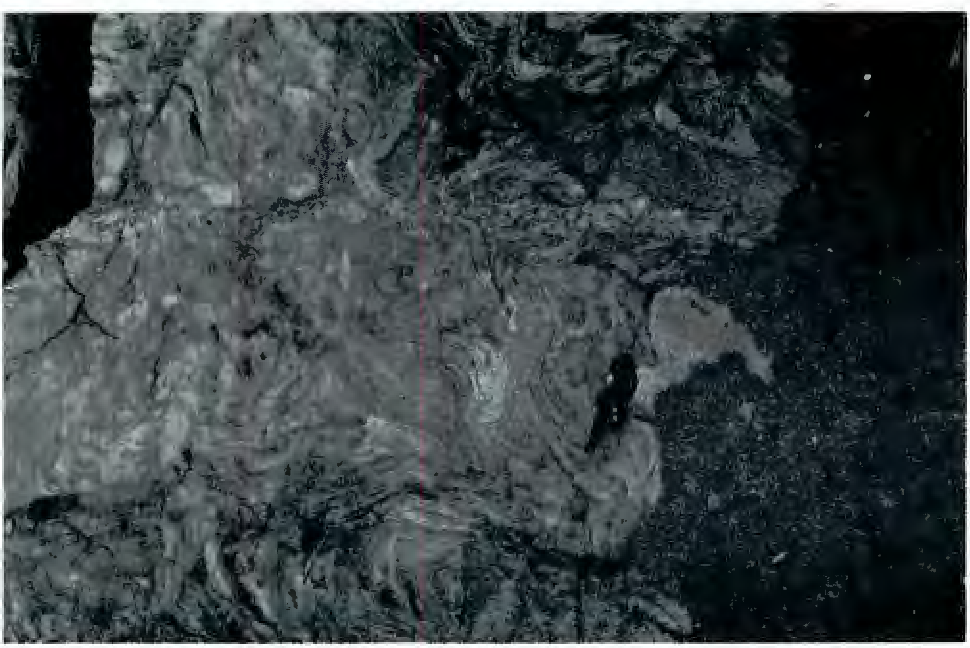


Plate VI. Disharmonic folding west of Witkoppie. The elements of the early folds can still be recognised, but now with curvilinear axial traces and the rocks appear to have been plastically deformed

It is possible that this deformation has been brought about by the major shear along the sides of which the disturbed gneisses occur, but it is more likely due to the presence of these younger granites for two reasons. Firstly, garnetiferous dyke rocks occur in a zone in the same area and late generation of staurolite in the schists in the same area point to the effects of the later granites. Secondly, the irregular folding at Haouseep is associated with ptygmatic folding of the banding and ramifying pegmatites.

The "Kromnek granite" of the Richtersveld is without doubt of the same suite as the younger granites of the present area and as suggested by De Villiers and Söhnge (1959, p.85), is provisionally correlated with the granites of the Richtersveld Igneous Complex dated as 850±20 My (De Villiers and Burger, 1967).

(v) Post-Stinkfontein granite

A fairly fine, even-grained reddish-brown granite, in places with xenoliths of quartzite along its contacts, was found intruded into the basal quartzites of the Stinkfontein Formation some six to seven km south of Lekkersing (2917AA). Macroscopically as well as under the microscope, this rock is exactly like the alaskitic granite described by Middlemost (1964, p.236-237) as forming ring D of the Rooiberg 2 Plutonic Complex of the Richtersveld. Middlemost records several modal values of similar granites which consist of microcline microperthite, quartz, a little biotite and minor plagioclase, ore, fluorite and white mica amongst the usual accessories and alteration products.

When the occurrence of granite was first found, a Kuboos age was accepted, but the absence of obvious phenocrysts and the similarity to a type of Richtersveld granite as described above, have rendered the correlation uncertain. However, the Richtersveld granite is sheared and traversed by dykes (De Villiers and Söhnge, 1959) and these features are absent in the Lekkersing occurrence even though it occurs in highly sheared rocks. Furthermore, the granite is also similar in hand specimen to the fine-grained facies of the Kuboos granite (Söhnge and De Villiers, 1948 and personal observation) and completely different in appearance from the granites described as "younger" above, so that provisionally, this granite is correlated with those of the Kuboos plutons dated as 550±20 My (De Villiers and Burger, 1967).

(b) Basic intrusives

North of the eastern part of the area now mapped numerous bodies ranging in composition from hypersthenites, gabbros, diorites to anorthosites occur in profusion and these have been amply described as noted before (Wyley, 1857; Kuntz, 1904;

Rogers, 1916; Strauss, 1941; Latsky, 1942; Söhnge, 1950; Read, 1952; Benedict et al., 1964; van Zyl, 1967 and Prins, 1970). These investigators all agree that the rocks are intrusive and Rogers (op. cit., p.103) drew attention to the fact that there is a general absence of megascopic chilled margins which he regarded as indicating that the upper limit of the zone of intrusion lay at considerable depth in the lithosphere during emplacement.

Strauss (op. cit., p.50) recorded that the ore bodies are post-granite and followed on the deformation of the area, but prior to N-S faulting. He further (p.51) stated that the zone of intrusion as a whole as well as individual intrusions or lines of outcrops all trend roughly E-W and was of the opinion (p.52) that the intrusions made room for themselves by means of forceful disruption of the gneiss rather than by stoping and assimilation. One of the ore bodies has been dated as 1.030 My (Benedict et al., 1964). In the Richtersveld many hornblendite and serpentinite bodies, older than the Vioolsdrif granite, are recorded (de Villiers and Söhnge, 1959; Middlemost, 1964, p.233). To the south of the area Jansen (1960, p.35) recorded the occurrence of gabbro and diorite while Pike (1959, p.26) found small bodies of pyroxenite and anorthosite which he considered as products of extreme palingenesis or metamorphic differentiation. He also noted that these bodies occur only in places away from any contact with the metasediments and that their age relationship and composition are similar to those of the granulites.

A great number of small bodies occur fringing the mafic belt from west of Kameelboom (2917DD) to Bodabeep (2918CD), both on the northern and southern sides. Many of these bodies are lenticular and arranged parallel to the strike of the foliation of the country rock and possibly represent tectonic lenses along the edge of the mafic belt, while others are roughly circular or elongate across the foliation and are almost certain intrusives. The norite bodies shown on Brink's (1950) map were examined during the present survey and these are all located within the paragneiss sequence and appear to be ultramafic bands while the list of mineral constituents (Brink, 1950, p.117) includes some which were found to occur as discrete bodies.

It is often impossible to decide whether the discrete mafic bodies are in fact intrusives as in some places they lie along lines in the gneiss and most probably represent remnants of bands of metavolcanics which have become disjointed during subsequent polyphase deformation and as they have been subjected to the same degree of metamorphism, they are mineralogically indistinguishable from the pyroxene granulites.

A peculiarity of the basic bodies is the presence of metamorphic veining of granitic composition which cut the mafic rocks only and their emplacement does not appear to have been governed by the regional foliation or banding.

As the basic intrusives resemble the pyroxene granulites in all respects it is not necessary to repeat the petrographic descriptions here. They can be classified as norites, hypersthene gabbros and bojites and develop biotite on shearing. Mineral composition found in the mafic intrusives are listed below.

Table 10. Mineral compositions of mafic intrusives

Specimen No.	Orthopyroxene	Clinopyroxene	Hornblende	Biotite	Plagioclase
75	x	x	x	x	x
77	x	x	x	x	x
131	x	x	x	x	x
76	x	x	x		x
84	x	x	x		x
93	x	x	x		x
132	x	x	x		x
403	x	x	x		x
268	x	x		x	x
345	x	x		x	x
124	x			x	x
125	x			x	x
181	x			x	x
636	x			x	x
486	x		x		x

Special mention is required of two of the basic bodies. The one is situated in a circular depression in the hills on the western side of Boesmanplaat (3018AB) where a soil-filled amphitheatre, similar to those resulting from the erosion of large kimberlite pipes, occurs within the hills with two small outcrops of the intrusive exposed. The rock is greyish brown, coarse grained, almost granitic in appearance and although it is a norite in composition, it does not resemble any of the other mafic rocks encountered. The other forms an elongate body west of Tafelberg at Matjesfontein (3018CD) and is banded along its edges with peripheral inclusions of metasediments. In thin section the central part of the body consists of hypersthene gabbro while the peripheral hybridised rock is of monzonitic composition consisting of orthoclase, some perthite, biotite and augite with a little plagioclase, quartz, apatite, sphene and zircon.

Hypersthene-bearing bodies were not found in the western part of the area mapped except for one small, possibly intrusive mass on Harras (2917AD) just north of the Stryd River. Furthermore, the intrusives found in the eastern part of the area are not all hypersthene-bearing. Several small lenses of light to dark grey fine-grained diorites were encountered in several places in the north-eastern part of the area and these consist of euhedral crystals of oligoclase or andesine, red-brown biotite with minor well-formed prisms of apatite and a little zircon. The rocks usually contain a little brown hornblende while chlorite and epidote are present as secondary minerals. Two of the specimens examined microscopically were found to contain a little brown hornblende while chlorite and epidote are present as secondary minerals. Two of the specimens examined microscopically were found to contain a little uralitised clinopyroxene while another had some quartz.

A dark monzonite was found north-west of Platbakkies in the vicinity of lamprophyre dykes with the same mineral composition and probably associated with them. It is a fine-grained, sugary-textured, dark brownish-grey rock and weathers to rounded brown boulders. Under the microscope it is seen to consist of large plates of untwinned potash felspar and small subhedral crystals of oligoclase, but these minerals also occur in the matrix with quartz, containing many flakes of red-brown biotite, a fair amount of green hornblende with accessory ore, apatite, zircon and sphene.

Along the shear zone on the northern side of Rietfontein (2918CC) several small dark bodies occur and as they have been sheared since their emplacement, the alteration will be discussed later. Similarly, in the large shear zones in the north-western part of the area, lenticular basic bodies are of frequent occurrence and as they have the same composition as the amphibolite dykes of the coastal flats and the intrusives into the basal part of the Stinkfontein Formation, they are discussed below.

The intrusive body found in the north-western corner of Nieuwefontein (2917AA) is a coarse black rock consisting mostly of large oikocrysts of hornblende in a fine-grained matrix of equidimensional grains of andesine. The only other minerals present are ore and apatite, the latter mineral forming fairly large prisms. A number of other basic rocks which have been found in the western part of the area are now composed only of chlorite and saussuritised felspar while the basic rock forming a small intrusive body on Kaavlakte (2917AD) is also so altered that it is impossible to determine its original composition, but some of the plagioclase forms euhedral crystals which are distinctly zoned with andesine cores and rims of oligoclase. The dark minerals are chlorite and fibrous amphibole with much ore, some calcite and a little quartz.

(c) Leucocratic intrusives

Benedict et al. (1964) described anorthosites associated with the copper-bearing ore bodies to the north of the present area and to the south Pike (1959, p.27) also found six small occurrences described as anorthosites consisting of over 85 per cent andesine. Pike mentioned that they have aureoles a few feet wide resulting in the formation of pink felspar, chlorite and veins of epidote in the surrounding gneisses. He was able to prove that these bodies are pre-Nama in age.

In the present area similar small bodies consisting mostly of plagioclase were encountered in a prominent shear zone on the northern side of the farm Rietfontein (2918CC). Other similar bodies were found six kilometres south-west of Gamoep and another between Rondegat and Bokputs (3018AB). As these bodies are small, they cannot be distinguished on aerial photos and it is thought that there must be many more which were not found during the survey.

The anorthosite bodies are usually circular in outcrop and are coarse greyish-white granitoid rocks which weather to a reddish-brown colour. In thin section the texture of these rocks is seen to be heteroblastic and they consist almost wholly of andesine, which often also forms larger porphyroblasts of antiperthite, and very few tiny flakes of greenish biotite, some ore and occasionally zircon. In one specimen examined the ore is rimmed by sphene while small amounts of interstitial quartz are found in some of the rocks.

(d) Dyke rocks

A wide variety of dykes have been intruded into the gneisses of Namaqualand at various stages during their deformation and as they assist in deciphering the polyphase deformation of the area, their relationships will be discussed in sequence of probably age, the oldest to be discussed first.

(i) In describing the oldest recognisable sheet-like bodies, it is not implied that even older dykes do not occur in the area. Some of the dark streaks in the gneisses may well prove to be attenuated and disjointed mafic intrusive sheets.

In the south-eastern part of the area two specimens were collected from narrow north-northwest-striking bodies taken to be dykes, while another forms a sill-like body on the western side of Anegas Mountain (3018AA). The dykes, which can be traced along strike for relatively short distances only, consist of large anhedra of labradorite and antiperthite, untwinned potash felspar with red-brown flakes of biotite, brown hornblende and altered, faintly pleochroic hypersthene. The hypersthene encloses small grains of zircon, hornblende and apatite and is rimmed by fibrous alteration products. Ore is present as an accessory mineral. One of the dykes also contains a little quartz and some myrmekite. The rock forming the sill consists of a granoblastic mosaic of clinopyroxene, andesine, orthoclase, hypersthene, biotite with accessory hornblende and ore. Like many of the small mafic intrusives, these rocks resemble the pyroxene granulites in all respects and can only be distinguished when they appear as narrow sheet-like bodies within the more leucocratic gneisses and it is quite possible that there are many more representatives of the old dykes, but if they occur in the mafic rocks, they would not be recognised.

(ii) Another group of dykes striking north-east has been emplaced along the foliation planes of the host gneisses in the Nombies (2917AD) area and they have been intruded by pegmatites since their emplacement. One of these dykes is a greenish-grey schistose rock with distinct banding parallel to the schistosity. In thin section it is seen to consist of orthoclase, quartz, some oligoclase containing a large number of small flakes of green biotite, chlorite, much ore, often with rims of sphene as well as apatite, small clusters of tiny epidote crystals, zircon and a little fluorite. In another less-sheared specimen, but also showing strong preferred orientation of mafic minerals, the potash felspar is microperthite and the rock is without chlorite and fluorite. The biotite in this rock forms tattered aggregates with small flakes surrounding larger books of biotite.

An east-west-striking sheared diorite dyke consisting of uralitised augite, fresh hornblende, andesine, quartz, ore and sphene was collected on Silverfontein (2918CC).

(iii) In the vicinity of Platbakkies (3018AD) a few altered dykes composed of fine-grained black rocks have been found striking north-northeast. The rocks have granoblastic textures and are composed of brown hornblende showing dimensional orientation, pale green fibrous amphibole, chlorite, small evenly distributed grains of ore and some apatite in a dense completely altered felspathic matrix. The ore grains are rimmed by sphene in some cases and patches of epidote and calcite form as a result of the alteration of felspar. In one of the specimens the plagioclase was determined as labradorite, but this rock also contains porphyroblasts of antiperthite to be seen even in hand specimen. Farther west in the Wildepaarde Hoek (2917DC) area, dykes occur also striking in a north-northeast direction and they are quite distinct in the field from the gneisses they traverse. In thin section, however, they are very similar in composition to the gneiss except that they contain greater amounts of biotite, ore, sphene, apatite and zircon. These dykes consist mainly of microperthite, microcline, microcline-microperthite, quartz, oligoclase and green biotite.

One of these dykes can be followed from Wildepaarde Hoek for many kilometres to the north-northeast and several outcrops occur along its strike. South of Sannagas (2917DC) the dyke rock along the same line of strike consists of euhedral crystals of oligoclase, much brown flakes of biotite and fairly prominent apatite. The felspar is saussuritised to yield epidote, quartz and chlorite, but the rock does not contain potash felspar. That these dykes are comparatively old is proved by the shear zones across the dykes in at least two localities, converting them to dark schistose rocks.

(iv) Dykes striking north-northwest or north-south are common in the area and west of the escarpment on the coastal plains, the region has been intruded by numerous mafic dykes, in some places occurring in swarms, all striking in more or less the same direction, but some of the dykes belonging to this group strike north-northeast. Rogers (1915, p.97) described these dykes while de Villiers and Söhnge (1959, p.138-145) have found these gabbroic, perknite, quartz diorite and quartz syenite dykes to be older than the Kuboos granite, but some of them cut the rocks of the Rooiberg Igneous Complex. They also (op. cit., p.138) described the dykes as being of two ages; mafic to ultramafic dykes were followed and transected by dykes of basic and intermediate composition. As in the case of the present area, the dykes of the Richtersveld are essentially vertical, were intruded along existing major fractures where rejuvenation of movement resulted in the shearing of many of the dykes.

To the north-east of the present area, Gevers et al. (1937, p.34-36) found diabase, gabbro, altered lamprophyre, microsyenite, syenite aplite and bostonite dykes in the area mapped by them. The diabase and gabbro dykes, recorded as striking north-east to north-northeast, are pre-Nama in age, cut all the pegmatites and are displaced by post-Nama faulting. To the south of the present area Pike (1959, p.32) found two narrow en echelon veins of lamprophyre and consistent with the findings in the present area, there is also a great increase in the number of dykes towards the west in the region to the south (Jansen, 1960, p.36-49).

During the present survey it was found that these dykes attain their widest distribution between longitudes 17°15' and 17°30'E, that they are found, although in reduced numbers, over the whole of the eastern part of the area mapped, but that they appear to be absent in the westernmost parts near the coast.

The most impressive dyke found in the area starts at Bitterfontein (3018CD) and crops out intermittently along its north-northwest course from there to east of Garies where its line of strike is offset en echelon fashion to the west and it leaves the area south of Koornhuis (2917DD) and continues to the north-northwest to cross the hill of Koornhuis beacon and from there was followed for another six kilometres. Brink (1950, p.214-216) first described this occurrence as the Houmoed dyke after the farm on which it occurs and followed the 10 metre-wide outcrop for a distance of at least half-a-mile. The dyke is composed of a black medium-grained dolerite which weathers to red-brown rounded boulders and can easily be followed even in areas lacking in outcrops by the red soil yielded by the dyke. West of Brandberg (3018CA) it is displaced by an east-west fault. A specimen from this locality shows well-developed ophitic texture with zoned laths of labradorite-andesine and zoned augite crystals with pigeonite cores. The rock also contains much ore, a little uralite, bent flakes of biotite, interstitial quartz and a little apatite. Brink (op. cit., p.216) noted that the zoned pyroxenes are typical of the Karroo dolerites as described by Nell and Brink (1944), but it is now known that all these dykes are pre-Nama in age.

Most of the dykes found in the eastern part of the area are lamprophyres and very many of them have been sheared since their emplacement due to rejuvenation of movement in the fractures along which they have been emplaced. The dykes are usually vertical or have steep dips towards the west, but occasionally small sills are encountered. In the east they are mostly less than one metre wide, rarely up to 2 metres, but towards the west they increase considerably in size. Even the thin lamprophyre dykes tend to be very long with outcrops along the strike for many kilometres.

The lamprophyres are red-weathering, light to dark grey, fine-grained rocks. They have allotriomorphic-granular textures and consist of orthoclase, microperthite or microcline-microperthite, oligoclase, green, sometimes idiomorphic crystals of hornblende, brown biotite, ore, apatite and zircon. One specimen collected contains a little pale yellow clinopyroxene and when the dykes are sheared, aligned flakes of biotite are prominent, quartz with undulose extinction appears with muscovite, chlorite, epidote and clinozoisite. These rocks are usually fissile with shimmering fracture surfaces frequently with strongly developed lineation due to shearing. Mortar structures are formed in the sheared specimens and in all of them sphene is found mantling granulated ore grains.

One of the lamprophyres collected at Soutfonteinkop (3018CC) is fine grained and black with prominent white felspar phenocrysts which are seen under the microscope as equant untwinned potash felspar euhedra.

An interesting occurrence of aplite dykes and sills was first encountered at Joumat and Kom Vleis (2917AC) where the sills tend to follow the east-west north-dipping foliation in the gneisses, but in places also cut obliquely across the rocks. Dykes of similar composition trending to the north-east also occur at this locality. Similar dykes were again seen to the west of Steenbok beacon (2917AC) from where they continue in a north-northwesterly direction to Breekhoorn. Another similar dyke-rock was found to the south of Koornhuis (2917DD). These rocks are light to reddish brown, fine grained and when sheared, exhibit a vague foliation. Under the microscope they display a xenomorphic texture and are seen to consist of microcline, microperthite, oligoclase, quartz with evenly-distributed euhedra of ore. Biotite occurs only as an accessory mineral together with apatite, sphene and zircon. One of the specimens was found to contain a little garnet and fluorite.

The other dykes encountered on the coastal plains below the escarpment are similar to those described by de Villiers and Söhnge (1959, p.138-145) and their descriptions need not be repeated here. It should be mentioned, however, that many of the dykes are now amphibolites, sometimes strongly banded and lineated, consisting of green hornblende, much quartz, some plagioclase, ore, sphene and apatite. Chlorite is a common constituent, often as bent flakes. In some specimens green hornblende is being replaced by blue-green amphibole and these rocks also contain epidote.

Of interest is the occurrence of garnet in some of the specimens of dykes collected; these occur in a zone from Meidjes Karroo (2917AC) to the north to Hardevlakte and Haouseep (2917AA and AB) and it is certain that many more of the dykes are garnetiferous, but as the garnet is inconspicuous, it is not always noticed in the field. At Meidjes Karroo one dyke with prominent garnet idioblasts, up to 1 cm across, was encountered. Under the microscope the garnets are seen as idioblastic crystals enclosing numerous small grains of felspar, quartz, hornblende, biotite and even epidote. In a sheared dyke from Hardevlakte the garnets are cracked and altered around crystal peripheries and along cracks.

There can hardly be any doubt that these dykes were emplaced over a long period of time; perhaps initial irruption took place just after the 1000 My metamorphic episode to post-Hilda times (McMillan, 1968, p.131), but was terminated prior to the deposition of the Nama sediments. One of the dykes has been dated as 878±41 My (De Villiers, 1968, p.35) and they also transect the Rooiberg Igneous Complex dated at 850±20 My (De Villiers and Burger, 1967). In the present area they have been intruded into the Stinkfontein Formation, forming large irregularly-shaped bodies between the basal part of the sediments and the underlying gneisses, but dykes are also found transecting the Upper Stinkfontein Formation. The lavas, agglomerates and tuffs in the Upper Stinkfontein Formation were most probably derived from the dykes and since lavas do not appear in the lower part of the Stinkfontein Formation, the period of vulcanicity as distinct from the period of emplacement of the dykes, occurred after the deposition of the Lower Stinkfontein Formation.

The emplacement of these dykes is structurally controlled and is closely associated with some of the episodes of deformation discussed later.

(v) Dolerites of the Vanrhynsdorp area strike east-west and Rogers (1904, p.31-32) described them as closely resembling the Karroo dolerites. Pike (1959, p.39) described similar dykes which he tentatively correlated with those of the Karroo, but Brink (1950, p.216) stated that the east-west dykes mineralogically resemble the Western Province dolerites as determined by Nell and Brink (1944). To the north and north-east of the present area De Villiers and Söhnge (1959, p.186-188) found dolerite dykes which are post-Karroo in age, while von Backström (1967, p.47) recorded the presence of four east-west dolerite dykes to which he assigned a Karroo age on petrographical grounds.

Apart from the dykes found by Brink, east-west dolerites were found in the present area in the Soutfonteinkop area and farther north at Groothoek (3018CC) and again in the western part of the area across the hills of Aardvark beacon (2917AD) and south-west of Chabiesies (2917AB). The petrology of these dolerites is so well known and again aptly described by Brink (1950, p.214-216) that their description need not be repeated apart from recording that the dykes are comparatively thin so that exposures are not continuous. Nevertheless, although the dyke south of Soutfonteinkop is less than one metre wide, it can be followed for a distance of more than six kilometres. It should also be mentioned that an east-west dyke from west of Groothoek was determined to be a lamprophyre.

Patches of black fine-grained dolerite occur on the eastern edge of the Bushmanland Plateau on the farm Vaal Puts (3018AB). The explanation for this occurrence is probably that the dolerite intruded as a sill between the sediments of the Karroo and their basement, and that the sediments have been stripped by subsequent erosion. On the map of the Nieuwoudtville area (von Backström, 1960) sheets of dolerites are shown in some localities occurring at the base of the Karroo sediments.

Brink (1950, p.215) noted that, with the one exception described previously, the dolerites follow the structural grain of the basement rocks. However, the dykes in the north-west of the area strike east-west across the foliation in the gneisses and it is clear that they were introduced along zones of weakness resulting from a post-Nama deformation in the area. Cox (1970, p.219-220) noted that "igneous activity was in evidence in one part or another of southern Africa throughout almost the entire time-range from 200 to 100 My", but that "it would be convenient to restrict the term 'Karroo' to those lavas of southern Africa which are of Jurassic age". In summarising the ages determined on dolerites, Haughton (1970) stated that their ages range from 190 to 150 My, i.e. Upper Triassic to Middle Jurassic, but while the earliest Kaoko lavas were extruded synchronously with those in the eastern part of South Africa, the peak of volcanic activity in the west occurred later during Lower Cretaceous times. McDougall (1963) also found that the ages of the dolerites range from 151 to 190 My, a range also indicated by the determination on palaeomagnetism.

(e) Pegmatites, aplites and quartz veins

North of the present area Gevers et al. (1937, p.25) described "a well-marked belt approximately 10 miles wide representing the contact zone between a very complex and varied series of older rocks and the younger Namaqualand granite-gneiss area on the south. There is a profusion of pegmatites along practically the entire length of the contact zone. Generally there is no sharp contact, but a broad contact zone, often a few miles wide, marked by xenoliths of the older rocks in the later Namaqualand granite-gneiss and intrusive lenticles of the latter in the former." This zone continues into the south-eastern part of the Richtersveld (De Villiers and Söhnge, 1959, p.91-94) where the pegmatites are concordant with a regional schistosity of the rocks invaded. They also noted (p.92) that the pegmatites do not strike parallel to the zone which is almost east-west, but that they strike between north-west and west-northwest.

In the present area the pegmatites are most numerous in the area from Chabiesies (2917AB) to Hardevlakte (2917AA) where they disappear under the sediments of the Stinkfontein Formation, but they are also prominent farther south in localities as indicated on the map of the western part of the area. The pegmatite belt as described by Gevers continues to the east and Hugo (1965, p.20) described a gently curving belt in the Kenhardt and Gordonia districts as being between 10 and 15 miles wide and 190 miles long. Although Hugo stated that the belt disappears in the southern part of South West Africa, it appears to be continuous from Putsonderwater in the east to the present area, a distance of some 350 km, forming a crescent-shaped zone around the north-western, northern and north-eastern limits of the Namaqualand gneisses.

Benedict et al. (1964, p.251-254) divided the pegmatites into "Old, Replacement and Young" pegmatites. From the descriptions it would appear that the old pegmatites are those which, in the present area, have been emplaced along shear zones or leucosomes in the coarse migmatitic rocks. The migmatitic banding has been described in connection with the dark porphyroblastic gneisses above, while the pegmatites emplaced along shear zones are common all over the present area and as the strike of the shearing occurs in several directions, the directions of strike of the pegmatites vary accordingly. It also follows that a wide discrepancy in the ages of these pegmatites can be expected and that they are not necessarily always 'old'. In the coastal regions, where the later phases of shearing are much in evidence, it can be clearly demonstrated that pegmatites were emplaced before, during and after the various phases of shearing and that their relative ages would be largely coupled with periods of shear deformation.

The age of the muscovite of the pegmatite from the Kamma River in the southern Richtersveld (De Villiers, 1967, p.40) determined on K/Ar ratio is given as 598±25 My and may give an indication of the younger ages to be expected. In this case, however, the age is almost certainly too low as movements approximately synchronous with the emplacement of the pegmatites, must have taken place prior to the deposition of the Nama sediments, generally accepted as being about 600 My in age (Martin, 1965, p.116).

The so-called replacement pegmatites of Benedict et al. (op. cit.) are associated with the noritoid bodies and could possibly be similar to the leucocratic dykes found in the present area associated with basic bodies and described above. The 'young' pegmatites all appear to reflect an age of 900 to 1000 My (Nicolaysen and Burger, 1965; Burger et al., 1965).

Hugo (1965) came to some very interesting conclusions. The bulk of the pegmatites strike west-northwest and they are mostly discordant with the foliation in the gneisses, but many are also concordant. They appear to have been primarily controlled by fractures and joints where they have been emplaced in the pink gneisses and frequently exhibit drag folding in the wall-rock along their contacts. This latter feature indicates that they occur along zones of weakness produced during a phase of deformation. Hugo divided the emplacement of the pegmatites into two phases; firstly, the grey gneiss pegmatitic phase ascribed to a period of wide-spread regional metamorphism dated at about 1000 My and secondly, the so-called biotite granodiorite pegmatite phase in which simple pegmatites are intimately associated with granodiorite and which return ages consistently lower (890-937 My) than the pegmatites of the first phase.

De Villiers and Söhnge (1959, p.94) suggested that the metamorphism of the Namaqualand gneisses culminated in the intrusion of the Richtersveld granite and that the pegmatites are genetically related to this period of magmatic activity. Von Backström (1964, p.185) also mentioned the possibility of two cycles of pegmatitic emplacement and he (op. cit., p.124) ascribed the general north-west trend of the pegmatites to their intrusion along tensional joints and faults.

In the eastern part of the present area the pegmatites which are younger than those emplaced along shear zones most frequently strike north-south and lie along faults in that direction. The best example of two ages of pegmatites was found on the farm Banke (3018AD) where a pegmatite striking east-northeast and emplaced along a shear with left-lateral drag is cut by a north-south pegmatite along which the older pegmatite has been displaced approximately one metre. These observations agree with those of Benedict et al. (1964, p.253) who also recorded an age of 900 My for one of their 'young' pegmatites. This age is of importance as it possibly indicates the stage when the north-south fracturing in the area had already commenced. It also possibly coincides with the second phase of emplacement of pegmatites as envisaged by Hugo and mentioned above.

North of the pegmatite belt in the south-eastern Richtersveld the rocks which can be recognised as metalavas, appear to be completely different from the gneisses and schists south of the belt. A similar situation is described by Gevers et al. as mentioned above, while very much farther to the east, west of Prieska, Rogers and du Toit (1908, p.12) described the mineralogical changes undergone by the rocks of the Marydale. There the degree of metamorphism increases rapidly from north-east to south-west and rocks of clearly volcanic origin change into hornblende schists and granulites over a fairly short distance. The presence of staurolite, kyanite and sillimanite is recorded in the highly metamorphosed rocks to the south of the pegmatite belt.

When the ages of the rocks of the Prieska area as recorded by Nicolaysen and Burger (1965) are considered, a similar picture evolves. To the north-east of the pegmatite belt two ages, 2640 My and 2630 My, of granites intruded into Marydale metavolcanics are available, whereas ages returned by rocks within the pegmatite belt and to the south-west of it, all fall within 1000-900 My. It does appear therefore that the metamorphism responsible for the 1000 My age is manifested by the presence of the pegmatite belt coinciding with a fairly sharp change from almost unmetamorphosed rocks to gneisses and schists.

Leucogranitic dykes are encountered in a few localities in the present area and because of their white colour, they are very conspicuous when mafic rocks are traversed. These dykes are 30 metres wide in some places and stretch for long distances across the country. The rocks are even grained, granitoid and consist almost entirely of potash felspar and quartz, but they also contain a little plagioclase and accessory biotite and zircon while one of the specimens collected in addition was found to contain a little garnet. Wolframite appears to be associated with similar dykes in the Komaggas area.

Like the pegmatites, quartz veins also have a varied history and folded and strongly lineated quartz veins have been encountered in many localities all over the area. The most prominent quartz veins are associated with the major north-south or north-northwest faults as described by Brink (1950, p.205), but they also appear along nearly all the shear zones encountered in the area and float of vein quartz assist in tracing shear belts where exposures are lacking.

(f) Kimberlite pipes and melilite basalt plugs

Kimberlite and melilite basalt occurrences between Gamoep and Platbakkies and farther south have been known for many years and have been investigated more recently by several concessionaires in their search for diamonds. The occurrences were not investigated during the present survey, but as the assertion that their distribution is controlled by structures in the basement has been made, the following observations are relevant.

Taljaard (1937) thought that the melilite basalts occur as isolated patches resulting from the erosion of a sill emplaced between the Dwyka tillite and its basement. Gevers (1937) disagreed with Taljaard as he found that the bodies are aligned along zones of brecciation parallel to the coast of Namaqualand and that several occurrences of melilite basalt lie in the dissected area west of the edge of the plateau, well below the level of the pre-Dwyka land surface.

Since the work of Taljaard it has been proved that these occurrences form discrete bodies, and that they may extend upwards into the Karroo; during the present survey a melilite basalt dyke was found on Kamiebees (3018AB) and farther south a melilite basalt was found in kimberlite. Drilling operations during prospecting of kimberlite rocks have proved them to be pipe-like in shape and many of them have conical craters infilled with later sediments. In the area north-west of Platbakkies the greatest concentration of kimberlite pipes is found and although some of them occur on north-south faults, they appear to be concentrated along north-east lines. This possibility was confirmed by Mr. H. Jenner-Clarke (personal communication) who has examined these occurrences in great detail.

Similar pipes and plugs occur south of Garies, most of which lie just west of the western boundary of sheet 3018CC.

Haughton (1969, p.237-238) reviewed the literature and recorded that fossiliferous argillaceous and arenaceous sediments obtained from a pipe on Banke (3018AD) could not be precisely dated, but on the whole possibly indicated a late Cretaceous or very early Tertiary age for the sediments which filled the crater.

The prolific occurrence of kimberlites on the western edge of the Bushmanland Plateau confirms some of the conclusions reached by Dawson (1970, p.328) that kimberlites are abundant only on the post-Kibaran cratons and that the kimberlites of more youthful orogenic belts are non-diamondiferous, but during the present survey it could not be proved that they have been emplaced along major fundamental fractures.

V. SEDIMENTARY FORMATIONS

A. STINKFONTEIN FORMATION

During the investigation of the gneisses of Namaqualand the reconnaissance mapping was extended to the north-west to meet with the existing geological map of the Richtersveld (De Villiers and Söhnge, 1959) and rocks of the Stinkfontein Formation were encountered. The survey was to have stopped at the contact where these sediments overlie the gneisses, but as the deformation of the Stinkfontein Formation also involved its basement, it became necessary to map the full quarter-degree square in order to compare the structures of the basement with those of the cover rocks. Consequently, some 14 field days were spent in mapping the southern extension of the Stinkfontein Formation south of latitude $29^{\circ}00'$S and east of longitude $17^{\circ}00'$E and this work, together with a survey along the coast, forms the basis of a separate paper (Joubert and Kröner, in the press).

The Stinkfontein Formation was originally investigated and named by Rogers (1912, 1915) and further details were later given by van Biljon (1939). The most comprehensive study of the rocks and their position in the geological framework of the Richtersveld are presented by De Villiers and Söhnge (1959), followed by a discussion on the genesis of the formation (Middlemost, 1966).

1. Distribution

The rocks of the Stinkfontein Formation lie west of a line from the north-eastern corner of sheet 2917AA in the north to Grootmis trigonometrical beacon (2917CA) and the extension farther south. Coarse boulder conglomerates and white quartzites form the hill of Wolfberg beacon (2917CA) in the south, and the conglomerates crop out intermittently to the north marking the line of the base of the formation, until the hill ranges south and on Nakanas (2917AC) are reached. These hills are composed of white and grey flaggy orthoquartzite, locally with basal boulder conglomerates, but on their western side the overlying felspathic quartzites appear. The line of hills continue to the north across Gemsbokvlei to Oograbies (2917AA) where the basal parts of the succession disappear under the overlying felspathic quartzites only to reappear in the hills around Lekkersing in the north and around the inlier of gneisses at Vredefontein (2917AA). The contact of the upper part of the succession continues from Oograbies in a north-northeasterly direction into the Richtersveld as a strongly sheared and faulted zone.

2. Succession

The Stinkfontein Formation lends itself readily to a twofold division:-

(b) Upper Stinkfontein Formation - brown-weathering felspathic quartzites and arkoses with thin layers of volcanic rocks

(a) Lower Stinkfontein Formation - grey and white flaggy quartzites, locally with prominent boulder conglomerates at the base.

(a) Lower Stinkfontein Formation

(i) Boulder conglomerates have been described by de Villiers and Söhnge (1959, p.117-119) and by Middlemost (1966, p.88-89) and only certain features applicable to the present area need be mentioned. The patchy distribution of the conglomerates indicates that the boulders were washed into the sedimentary trough at intervals along its length resulting in great local thickness of these rocks and their absence elsewhere. At Wolfberg the pebbles and boulders have been flattened and elongated since their deposition while at Oograbies they appear to have been subjected to a second phase of deformation so that the individual boulders are now seen as curved elongate phacoids and bent quartzite discs in the sheared micaceous matrix.

(ii) Orthoquartzites. The prominent hills of the Stinkfontein Formation (Plate VII) are composed of hard, grey to white cross-bedded flaggy quartzites and have been ably described by de Villiers and Söhnge (1959, p.120). They vary tremendously in thickness and while they are only a few metres in thickness at Vredefontein, they attain great thicknesses in the hills at Lekkersing and Oograbies.

Plate VII. Hills capped by orthoquartzites of the Lower Stinkfontein Formation on Gemsbok Vlei

The present distribution of the orthoquartzites indicates that the trough receiving the sediments at the time of deposition had its greater dimension in a north-south direction prior to the deposition of the upper felspathic quartzites and that the shape of the basin changed during deposition so that the upper part of the succession now straddles the orthoquartzites and overlaps onto the basement across the orthoquartzites.

(b) Upper Stinkfontein Formation

(i) Felspathic quartzites are described by Middlemost (1966, p.91) and of the 70 samples collected by him, he identified 23 per cent as felspathic quartzites and 19 per cent as arkoses. They are readily distinguished from the orthoquartzites in weathering to a brown or red colour and do not crop out as flags and the contact is usually gradational over a zone a few metres wide.

(ii) Volcanic rocks, lavas and pyroclastics, appear in the Stinkfontein succession just above the top of the orthoquartzites and are again fairly prominent near the top of the sequence. These rocks have been described in detail by de Villiers and Söhnge (1959, p.121-124), by Middlemost (1966, p.92-95) and by Rogers (1915, p.85-86).

3. The nature of the contact between the Stinkfontein Formation and its basement

The junction between the quartzites with the gneiss is adequately described by Rogers (1915, p.84) and as the rocks on both sides of the contact are highly sheared, it is not always possible to locate the contact exactly. The refoliated quartzofelspathic gneisses resemble the sheared felspathic quartzites closely and distinction between the orthoquartzites and the metaquartzites of the basement is not always possible. However, there can be no doubt about the angularity between the strike of the foliation in the gneisses away from the contact and the line of contact between the basement and overlying sediments.

The sheared rocks of the basement below the contact contain small pods and aggregates of pegmatitic and vein quartz material which have become distorted and disjointed during shearing and now lie as phacoids in the plane of refoliation.

In the vicinity of Vredefontein mica schists, described by Martin (1965, p.89) as grading "into phyllites belonging to one of the phyllite zones of the Stinkfontein Formation" were found to represent highly sheared rocks of the basement exposed in the core of an anticline and surrounded by a narrow collar of orthoquartzites separating them from the Upper Stinkfontein Formation.

4. Deformation of the Stinkfontein Formation

The structure and tectonism of the Stinkfontein Formation, to be discussed in greater detail later, has been described by Joubert and Kröner (in the press).

Four episodes of deformation are distinguished; the first two episodes resulted when the Stinkfontein Formation was involved in gravitational sliding due to undulatory movements in the basement producing differential uplift and subsidence in the basin of deposition.

The earliest lineations, expressed as striations, elongated pebbles and small folds with curvilinear axial trends, usually only seen at or near the base of the formation, plunge at different angles down the dip in a westerly direction and appear to have resulted by the sliding of the sediments over an irregular surface into basins which were in the process of being deepened. These linear features of the first episode (F_1) were deformed during the later main episode of folding (F_2) and the associated shearing, but both these episodes can be related to the differential subsidence and uplift of the basement floor over a fairly extended period of time.

During the main episode of deformation the rocks were folded mainly in a north-northeast direction with a less strongly developed set of folds trending north-northwest. In the gneisses of the basement these fold trends can be seen to belong to a conjugate set of folds and at Wolfberg the less-strongly developed folds trending north-northwest have been expressed in kink banding of the sediments.

The folds of the main episode are usually fairly open, nearly symmetrical in shape and plunge gently to the south-southwest, north-northeast or north-northwest. They are seen to occur in zones between regions where the sediments are almost undeformed. The axial planes of the folds trending north-northeast dip on an average approximately 45 degrees to the west and are associated with strong axial planar cleavage and shearing so that sedimentary features are destroyed along the folded zones.

Shearing, which is most prevalent along the volcanic layers, resulted in the phyllonites found in the Stinkfontein Formation and is also responsible for the development of the down-dip lineation usually associated with such zones (c.f. Sutton and Watson, 1962, p.95-96).

Mild north-south trending monoclinal folds (F_3) with the shorter steep limb to the east and plunging gently to the north, deform the folds of the main episode and are again superseded by the final episode of deformation (F_4) mainly expressed in omnipresent closely-spaced, near east-west jointing, but locally also as minor foliation crenulations. Some east-west breccia faults are also encountered. This last episode of deformation can almost certainly be related to the east-west faults of post-Nama age and associated dolerite dykes, thought to be of Karroo age (190-150My; Haughton, 1970), traversing the basement rocks farther east and south-east.

5. The age of the Stinkfontein Formation

The mafic dykes cutting the sediments of the Stinkfontein Formation and its basement to the east (De Villiers and Söhnge, 1959, p.116 and 138-145; Middlemost, 1964, p.251-156) were almost certainly intruded after the orthoquartzites of the Lower Stinkfontein Formation had been deposited as indicated by the mafic intrusives at the base of the formation and by the presence of volcanic rocks being restricted to the upper part of the formation.

The mafic bodies which were emplaced in a number of places along the line of contact between the base of the Stinkfontein Formation and the gneissic basement, appear to have been unable to penetrate the basal part of the succession to any great extent, but these rocks do not represent lavas since they have small apophyses locally intruded into the orthoquartzites. Also, as there are no indications of volcanoes in the area, only the dykes could have served as feeders for the lavas and pyroclastic rocks in the Stinkfontein Formation. Vulcanicity was initiated almost at the same time as the commencement of the deposition of the Upper Stinkfontein Formation, but it is clear that the dykes, which have a fairly long history, were still being intruded even after the deposition of the sediments had ended. Only one of these dykes, a major dyke following the course of the Gannakouriep River in the Richtersveld, has been dated and is recorded by De Villiers and Burger (1967) as being 878±41 My in age.

As mentioned above, the trough where the sediments of the Lower Stinkfontein Formation accumulated had its greater dimension in a north-south direction as indicated by the present distribution of the orthquartzites. Most of the pegmatites in the present area, not associated with the shear zones, strike north-south (c.f. Benedict et al., 1964, p.253) and have been emplaced along existing fractures which possibly indicates that the north-south trough could have been initiated during or prior to the emplacement of the pegmatites. Nicolaysen and Burger (1965) record the age of monazite from a pegmatite at Springbok as ca. 950 My.

B. HILDA FORMATION

On the farm Klein Duin (2917AA) and on the western bank of the Kamma River, a small patch of dolomitic limestone, separated from the upper part of the Stinkfontein Formation by a thin conglomeratic grit, occurs on the eastern side of a major north-south fault. From the description in the report on the geology of the Richtersveld (De Villiers and Söhnge, 1959, p.126-137), these rocks belong to the Kaigas Formation and although the contact is sheared, they appear to rest conformably on the quartzites of the Stinkfontein Formation. However, the geology of the Richtersveld is at present being reappraised and the limestones directly overlying the Stinkfontein Formation in the southern

Richtersveld will in future be grouped with the Hilda Formation (Dr. A. Kröner, personal communciation).

C. NAMA SYSTEM

The term "Nama System" is used as general agreement on the nomenclature has not been reached. During the present survey no attention was paid to the sediments of Nama age as these rocks are being investigated at present (Germs, 1967, 1968) and they have been described, amongst others, by Rogers (1912, 1912a, 1915) and by Brink (1950).

The rocks of the Nama System occur in the south-eastern part of the present area and are again found north of Koornhuis as the southerly extension of the plateau west of Springbok. The southern point of the Nama rocks of the eastern Richtersveld just reaches across the northernmost boundary of the present area.

The sediments of the Nama System are flat-lying in most areas, but have been affected by minor folding and appreciable faulting since their deposition. Brink (op. cit.) found the folds trending parallel to the faults which strike almost north-south, while farther to the west, Kröner (1968) found earlier folds plunging north-northwest and south-southeast refolded by folds plunging north-east and south-west.

D. SUPERFICIAL DEPOSITS

Superficial deposits, except for extensive sand cover on the plains west of the escarpment and soil reaching in from the Bushmanland Plateau in the east, are remarkably absent and the present area lends itself to the examination of the Archaean gneisses.

Gritty clays and silts with silcrete in places, lie on kaolinised and altered gneisses along north-south fracture zones along and near the eastern boundary of the area around Platbakkies (3018AD). The sediments now form small conspicuously white or yellow hills and ridges and lie approximately on the level of the Bushmanland Plateau. They are believed to have been deposited along old river channels which followed the fractures at the time of the formation of the plateau.

In many places west of the Bushmanland Plateau, the valleys between the hills have been choked by thick deposits of red sandy soil so that some of the valleys display mature topography such as the wide valley sloping to the west from north of Dabeeb (2918CD) towards Rietfontein (2918CC). These valleys are at present being re-excavated from the west.

Small patches of surface limestone and kaolinite occur as remnants at some places along the hillsides and on shelves and possibly indicate the existence of an intermediate surface between the Bushmanland Plateau and the coastal plains or perhaps mark the position of a down-warped Bushmanland Plateau.

The larger dry river courses have terraces of sand and gravel along them and below the escarpment diamonds are being recovered in older gravels under the sand along the Buffels River. Several geologists have mentioned the occurrence of a few diamonds along the lower reaches of most of the streambeds leading into the Atlantic Ocean and while the survey was being conducted, prospecting along the upper reaches of the Buffels and Stryd Rivers as well as along the river course below Tafelkop (Swartdoring River, 3018CC) was in progress.

VI. TECTONIC HISTORY AND ASSOCIATED METAMORPHISM

A. GENERAL

Several phases of folding and deformation have been recognised in the gneisses of Namaqualand and have been numbered in succession F_1, F_2, F_3, etc. The succession of events and episodes was determined in the way described by Tobisch (1966, p.394) and is based on the following criteria: 1) folding of the axial planes and the associated lineation of earlier folds by the younger deformation; 2) style of the folds; 3) recrystallisation accompanying the folding and the associated degree of metamorphism and, 4) orientation of the axial planes of the folds.

Parks (1969) has questioned the validity of these methods employed in correlating structures in metamorphic belts and in a region the size of the present area such correlation may indeed be thought to be uncertain. However, it appeared that the abovementioned criteria could be used consistently and from the data observed there evolved a picture of the sequence of structural events and of the associated metamorphism for the whole of the area. There was no difficulty in distinguishing F_1 and F_2 folds by their style in regions outside of shear zones, but in these belts folds similar to those of the earlier episodes were formed and the distinction was not always possible. The folds of the later episodes, F_3 and subsequent deformation, could mainly be distinguished on direction of trend and on the associated degree of metamorphism, assisted by the style of folding. Again, apparent repetition of movement along earlier lines of deformation during a later phase of folding in places, invalidated the use of degree of metamorphism as a criterion in the determination of the sequence of phases of deformation. In so many localities, outcrops show two or even three parallel or almost parallel trends of deformation, thus complicating the unravelling of the structures.

The order of events of deformation of the Namaqualand gneisses is quite clear, though the sequence of the episodes constituting the second and the third events is obscured by repetition of movement along some of the lines of structural weakness. Thus, some of the episodes described as separate phases of an event possibly belong to one deformation; for example, F_5 and F_6 are possibly members of a conjugate set of folds although shearing along F_6 was seen as refoliation across F_5 shear zones. It will also be noticed that some of the episodes consist of more than one direction of deformation but, as in the case of F_8 comprising deformation along at least three different trends, they have been grouped together for they demonstrably belong to one phase of deformation. This division has been followed mainly to simplify correlation with events elsewhere and to ease any subsequent detailed investigation.

The major structures as mapped and the general disposition of the layering are shown in figs. 4-7. The net illustrated by Kröner (1968, p.26) was used for contouring the tectonic data on the synoptic diagrams.

B. SPECIAL SURVEYS

As the time available for the survey of this very large area did not allow for much detailed work throughout the area, four relatively small areas of good exposure and occurrence of mafic rocks were selected where the structural features could be examined with ease and in greater detail. These areas are situated

(1) on the eastern side of Banke (3018AD),
(2) the mafic patch between Elands Kloof and Hartebeest River at Witplaat (3018CB),
(3) Guaapseberg (3018CD) and
(4) Soutfontein (3018CC).

1. Banke

(a) The oldest folds (F_1) seen are in the nature of intrafolial folds (Turner and Weiss, 1963, p.116) as tight closures with axial planes parallel to the layering. They display thickened hinge zones with long tapering limbs and vary in size from less than a centimetre to less than a metre from limb to limb (Figs. 8 and 12), but large-scale structures of this type were not recognised. The direction and amount of plunge of these folds which are associated with the tectonic banding, could nowhere be determined.

(b) Folds (F_2) folding F_1 folds are commonly seen as large and small-scale structures. They are close to isoclinal (Fleuty, 1964, p.470) in style and are best displayed along the contacts on the eastern side of the mafic patch where the dark rocks reach out in long tapering folds onto the underlying acid gneisses (Figs. 9 and 11). The same structure is seen on the map, on a much larger scale, in the thin line of leucocratic gneiss separating the line of mafic rocks in the south from the main dark patch to the north. The axial planes of these folds are gently to moderately inclined to the north and the folds plunge gently to the north-west or south-east (Figs. 10(a) and (b)).

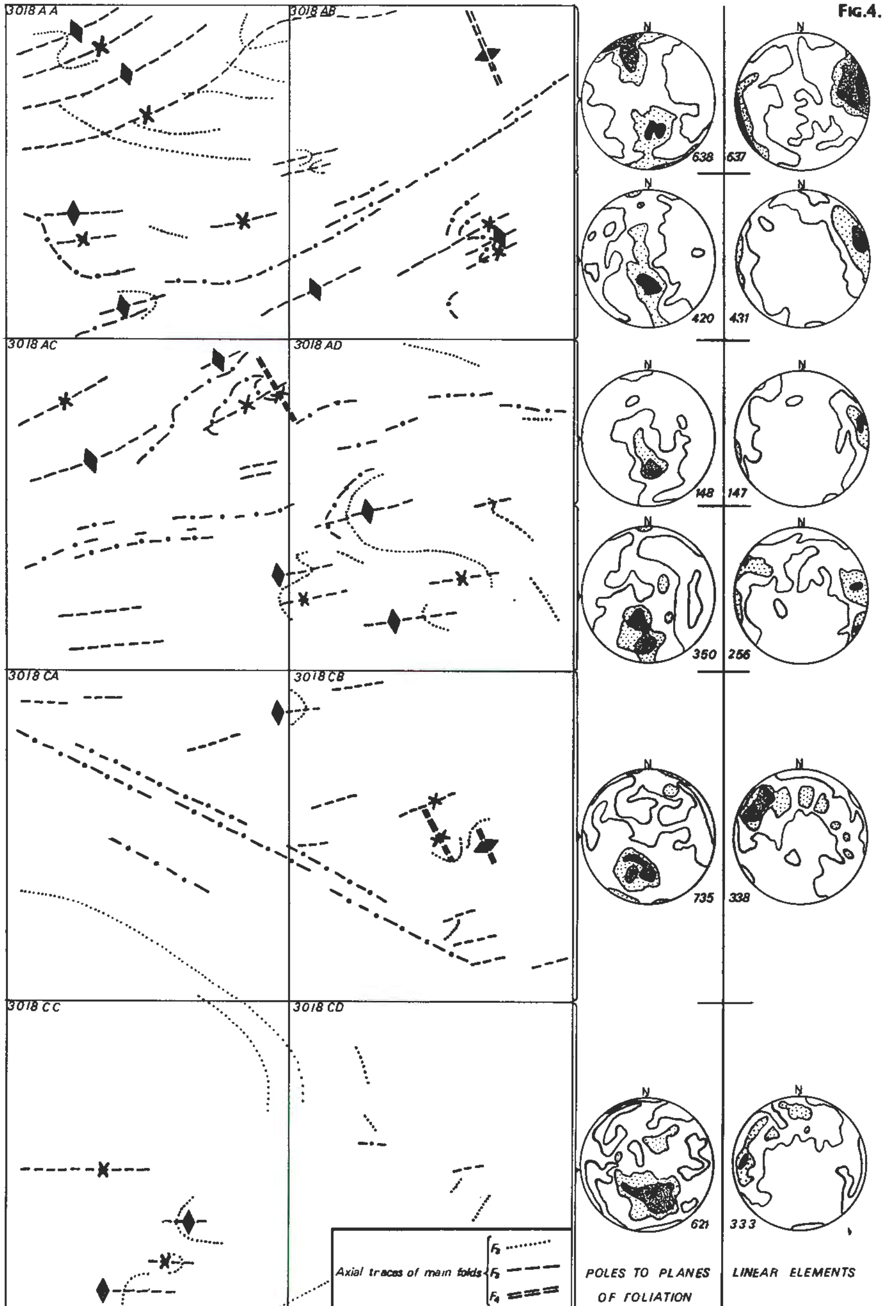


Fig. 4 — Structural data of the eastern part of the area. *Main shear zones* — · — · —

Numbers refer to readings plotted

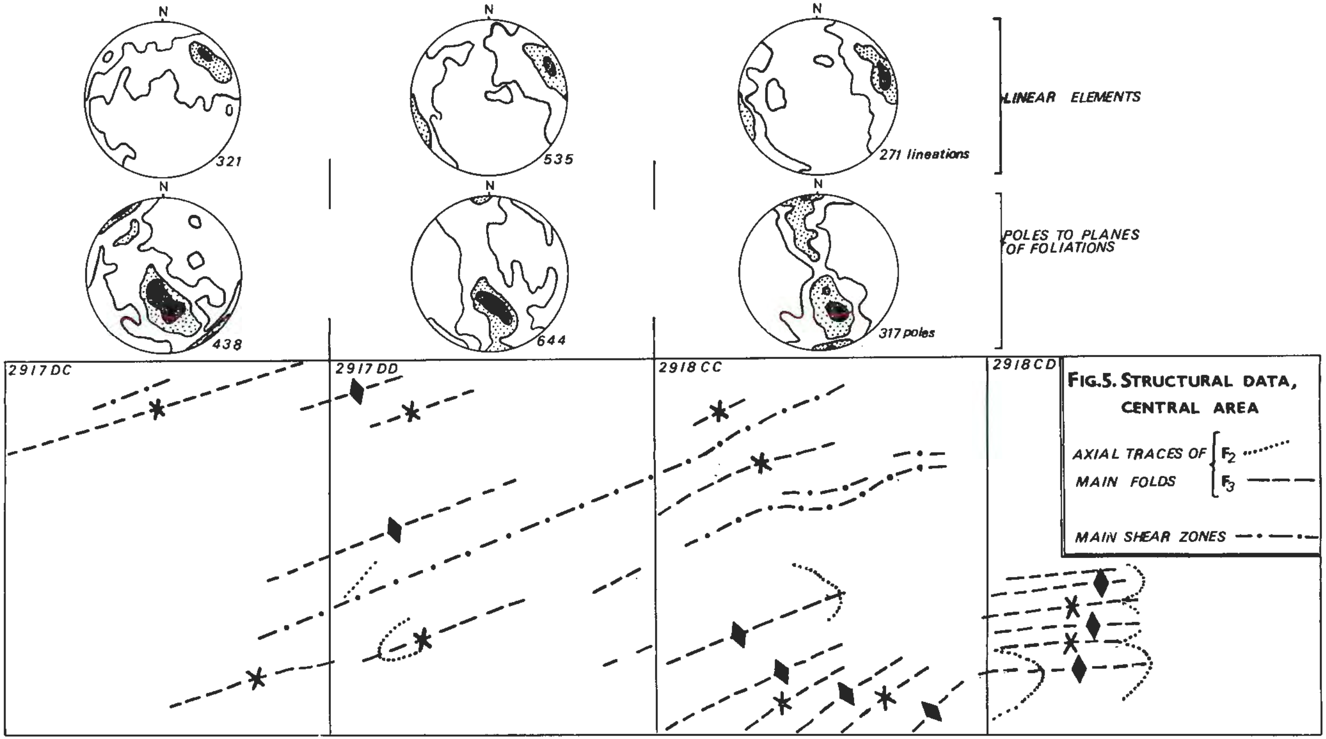


FIG.5. STRUCTURAL DATA, CENTRAL AREA

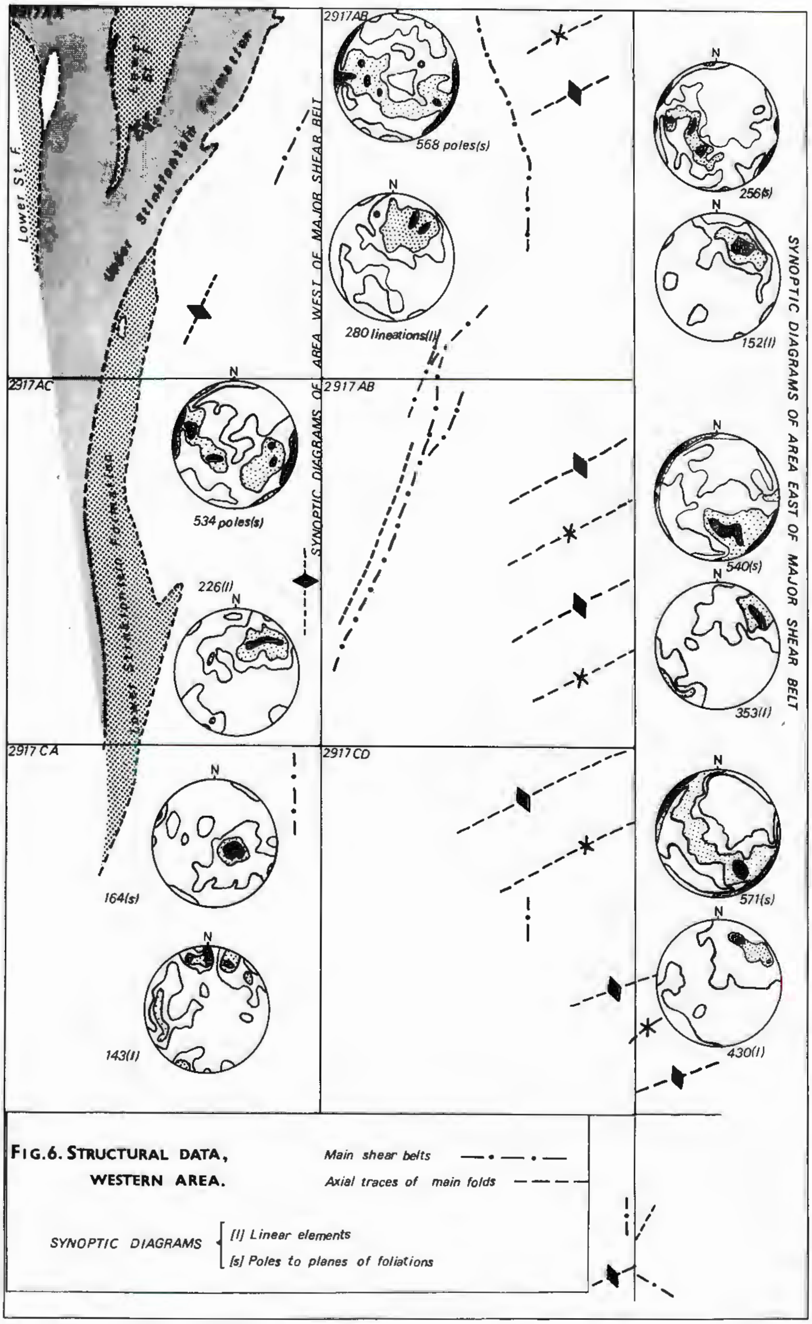


FIG.6. STRUCTURAL DATA, WESTERN AREA.

Main shear belts —·—·—

Axial traces of main folds — — —

SYNOPTIC DIAGRAMS
- [l] Linear elements
- [s] Poles to planes of foliations

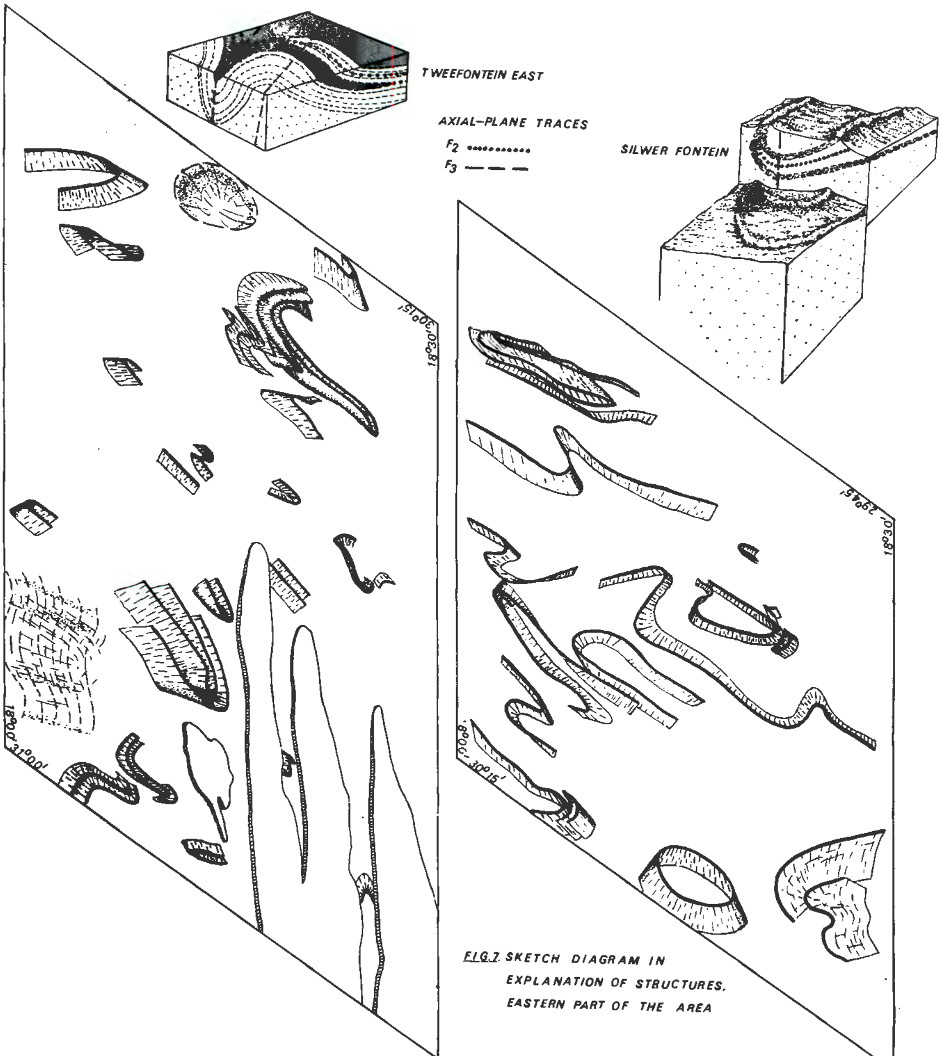


FIG.7 SKETCH DIAGRAM IN EXPLANATION OF STRUCTURES, EASTERN PART OF THE AREA

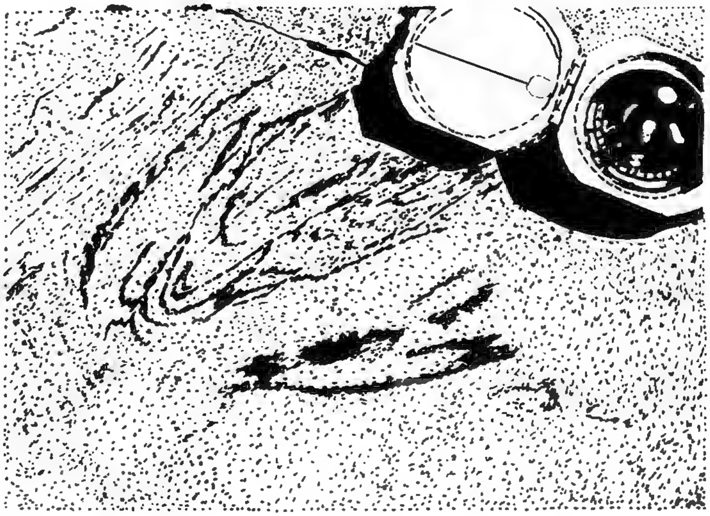


Fig. 8. Tight F_1 folds refolded during F_2 deformation seen in mafic rocks on Banke

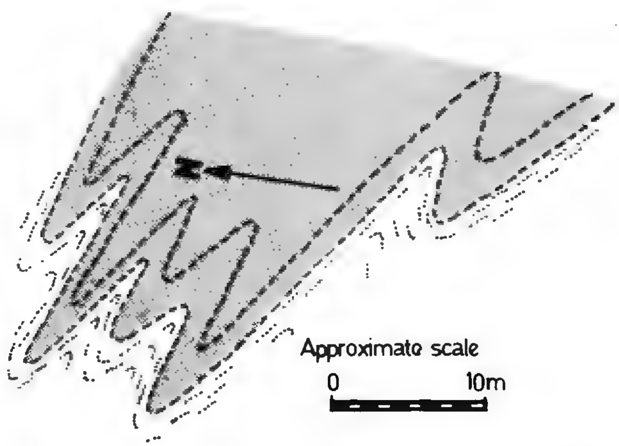


Fig. 9. Sketch of long tapering F_2 folds displayed as fingers of mafic rocks reaching into the acid gneisses on the eastern side of the patch of dark rocks on Banke

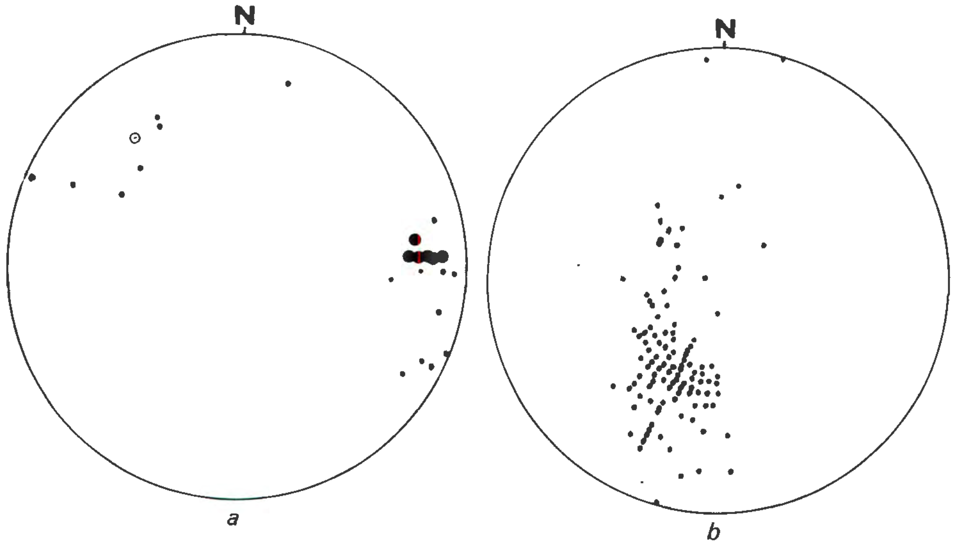


Fig. 10. Equal-area projection of the structural elements at Banke
(a) Linear elements; l_2, small dots; l_3, large dots; l_4, circles
(b) Poles to banding and foliation

Lineations as orientation of dark constituents are not well-developed in this area and unless occurring in narrow zones obviously related to the later phases of deformation, are always parallel to the axes of F_2 folds and are therefore of the same generation. Some of the congruent folds are less closely appressed and occasionally contrary dips of the foliation, i.e. to the south, are encountered. It was noticed that trains of crystals of garnet developed parallel to the layering and possibly in the axial planes of F_2 folds at this stage.

(c) F_3 folding resulted in open folds, refolding the earlier folds and F_2 lineation, trending almost due east-west, and their plunge, which is gentle and slightly to the north of east (Fig. 10(a)), is controlled by the pre-existing layering brought about by the earlier deformations. Deviation of up to 45 degrees in the direction of plunge in the F_2 lineations have been recorded as resulting from F_3 folding. A number of F_3 folds are monoclinal in style and they show strong refoliation along the southern steeper limbs of the folds where a lineation, usually as streaks of felspathic material, is developed parallel to the folds. On the western side of the main patch of dark rocks, folding of this generation results in the curvature of the folds of earlier phases of deformation (Figs. 11 and 12).

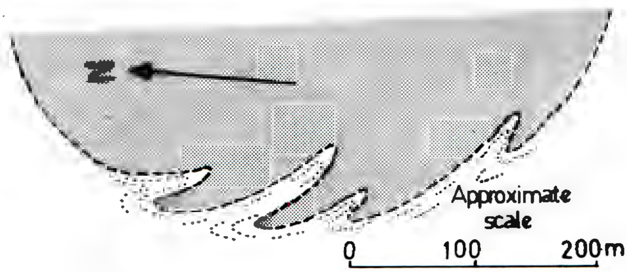


Fig. 11. Sketch showing curvature of axial planes of F_2 folds by folding about east-west axes on Banke

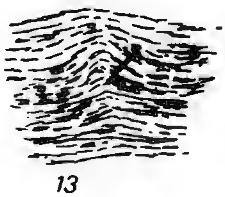


Fig. 12. Mild east-west folds of the third generation deforming F_1 folds on Banke

Fig. 13. Typical small-scale F_4 fold on Banke

The folds of the third generation are accompanied in places by strong east-west shearing.

(d) Mild folds (F_4) folding F_3 folds and trending north-west, curve the banding and are seen to deform the rocks over short distances only, as they die out along strike (Fig. 13). In one locality the strain-slip cleavage planes separate zones along which the foliation in the gneisses has been sharply contorted (Figs. 14(a) and (b)). The axial planes of the folds are near vertical, usually dipping steeply to the west, and the folds, because of the attitude of the pre-existing foliation, plunge gently to the north-west. Small shear zones along which a strong lineation of lenticular dark mineral aggregates occur plunging north-westerly, appear parallel to the axial planes of F_4 folds.

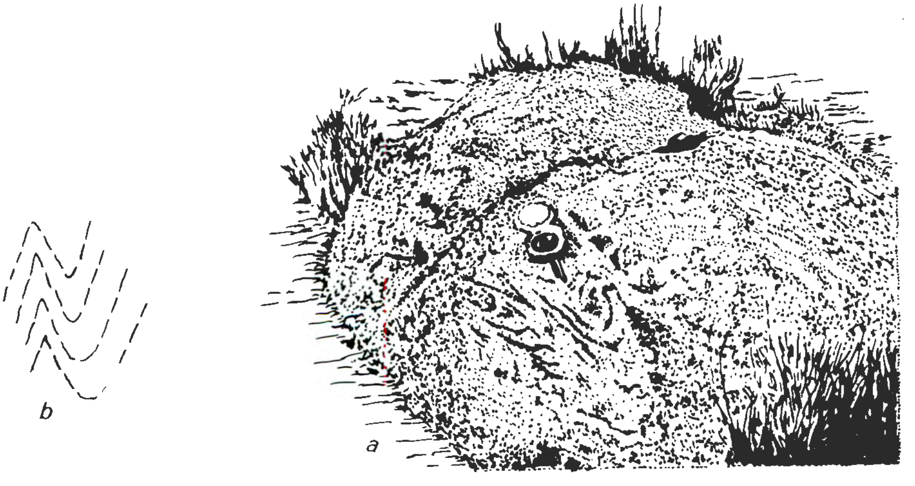


Fig. 14(a) Crenulations of the fourth generation in the augen gneiss on Banke

14(b) Schematic drawing of 14(a)

Small granitic veins are emplaced in zones parallel to the trend of F_4 folds which in some places do not appear to have been plastically formed and show signs of cleaving or refoliation in the axial plane direction. The layering in these folds is somewhat disjointed and dark minerals tend to aggregate while in some places clusters of garnet were formed.

(e) Minor shear zones in three different directions followed on the folding of the gneisses, all of which transect the granitic rocks. The oldest and most prominent strikes N65°W, the second

$N65^{\circ}E$ and the last $N35^{\circ}E$. Numerous joints, chlorite-filled fractures as well as a breccia fault, strike north-south.

2. Witplaat

The same folds as described for the Banke area are repeated at Witplaat, but with the difference that, although the F_2 folds and associated lineations still plunge fairly regularly, the foliations dip in all possible directions (Fig. 15(a) and (b)). F_2 folds are of the same style as those of Banke and the F_3 folds, usually fairly mild open structures, are more prominent here. Similar folds of the latter generation are seen for the first time (Fig. 16) and crenulation of the foliation between planes of slip are common (Fig. 17). Boudins (Plate VIII) are developed parallel to the plunge of F_3 folds and interference structures between F_2 and F_3 folds are seen on various scales (Plates IX and X).

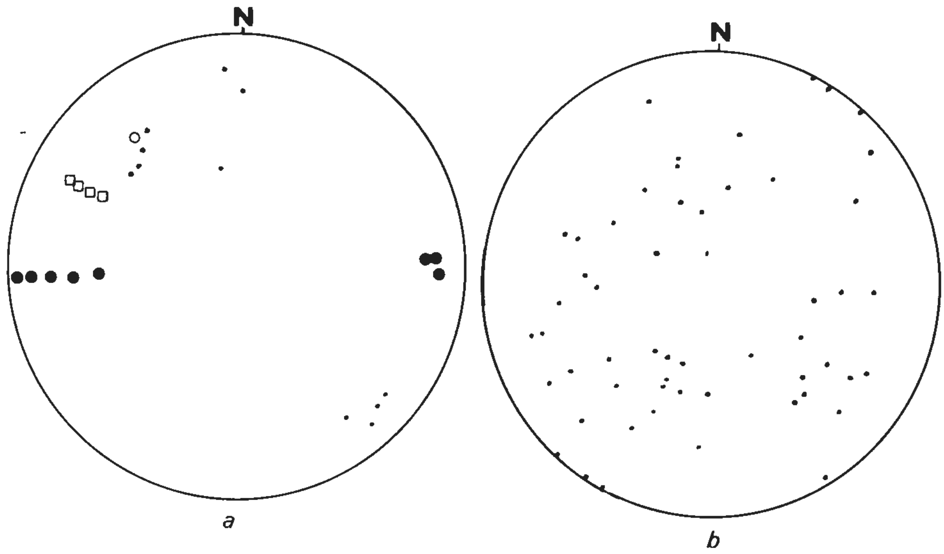


Fig. 15. Equal-area projection of the structural elements at Witplaat
(a) Linear elements; l_2, small dots; l_3, large dots; l_4, circles and l_5, squares
(b) Poles to banding and foliation

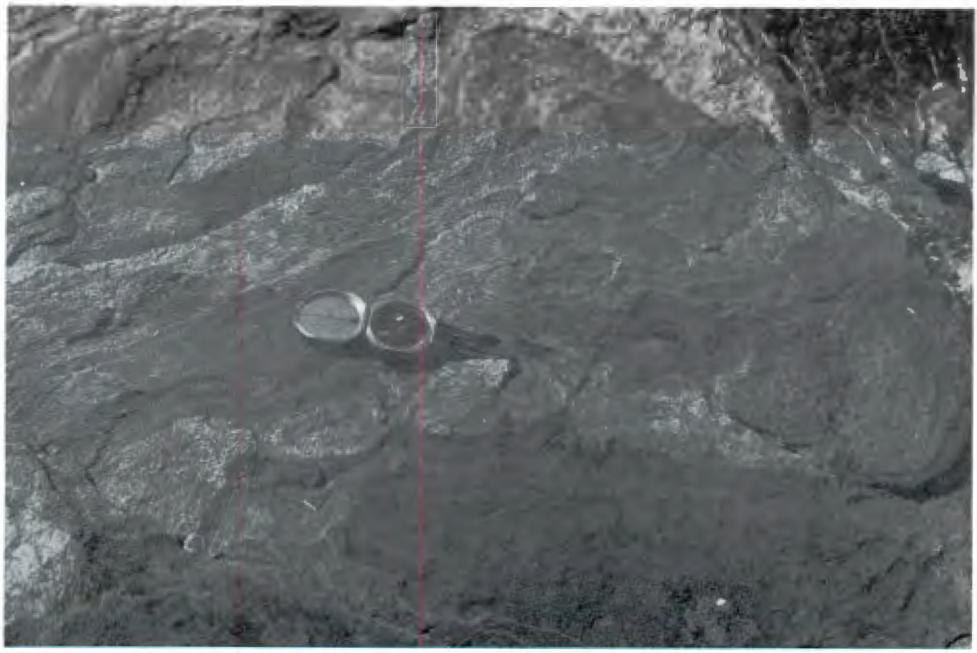


Plate VIII. Boudins of leucocratic rock in the mafic rocks of Witplaat

F_3 folds here have the same orientation as at Banke and the same also applies to the subsequent F_4 folds. At Witplaat F_4 folds are usually monoclinal with the shorter limb to the west (Plate XI). These folds die out along strike.

Shearing in a west-northwesterly direction as at Banke and the accompanying folds are prominently developed at Witplaat. In places the earlier folds are aligned to that direction and very complicated structures result (Figs. 18 and 40), but in a number of localities chevron-type folds were found (Figs. 19 and 20).

Shearing in a north-easterly direction is commonly seen as well as associated minor folding (Fig. 21) and these zones also have pegmatites emplaced along them, but at Witplaat they do not consistently strike N65°E; the majority, however, conform to that direction.

Minor crenulations of the foliation have been found along zones trending north-northeast and the presence of numerous north-south vertical joints and chlorite-filled fractures was recorded.

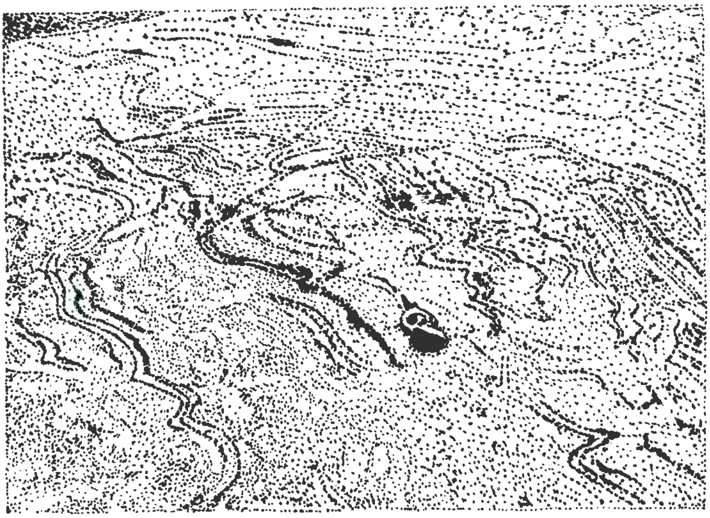


Fig. 16. Similar folds of the F_3 generation in the banded mafic rocks at Witplaat

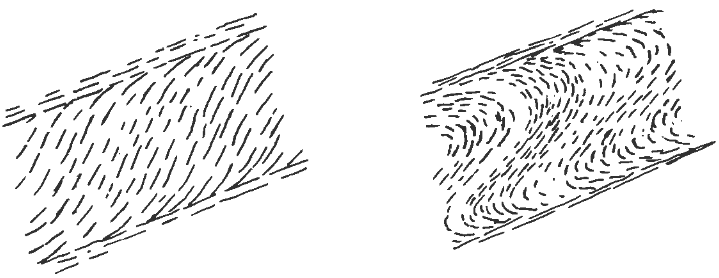
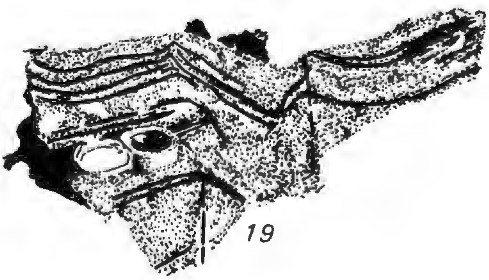


Fig. 17. Development of crenulation of the foliation during F_3 deformation at Witplaat

Plate IX. Interference structures developed by superposition of F_3 deformation on F_2 folds at Witplaat

Fig. 18. Contortion of folds of the earlier generation by movement along planes of slip in a west-northwesterly direction at Witplaat

Plate X. Interference structure developed by superposition of F_3 deformation on F_2 folds at Witplaat



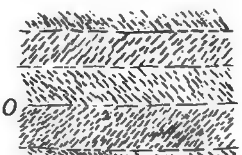


Fig. 19. Folds resulting from movement along planes of slip in a west-northwesterly direction at Witplaat

Fig. 20. Chevron-type folds in a west-northwesterly direction at Witplaat

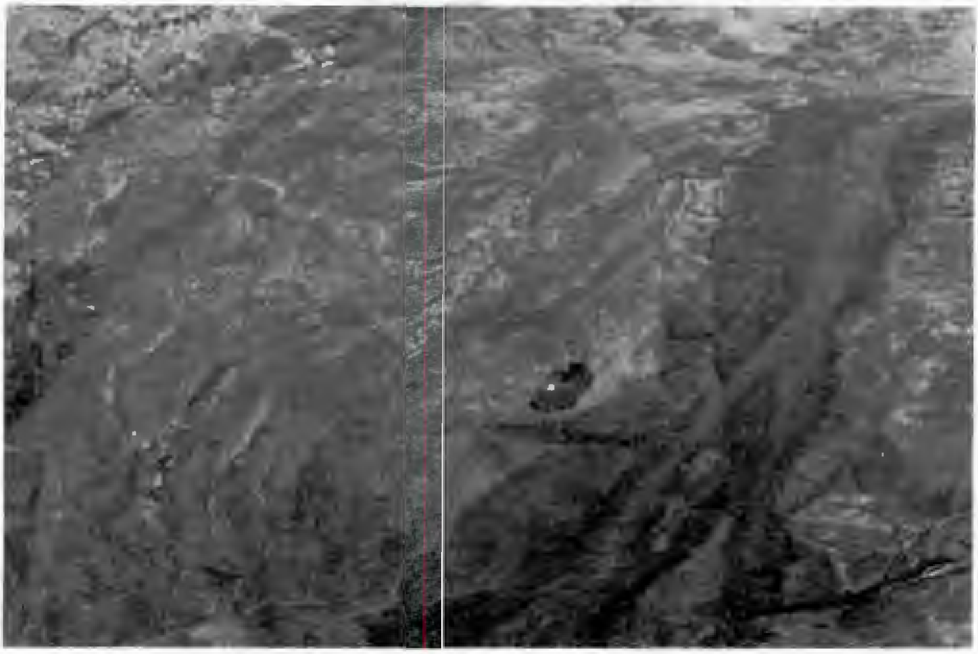


Plate XI. Monoclinal fold of the F_4 generation in the mafic rocks at Witplaat

Fig. 21. Minor folds with axial planes trending north-east at Witplaat

3. Guaapseberg

In the southern part of the basement inlier between the Nama sediments, to the south of Guaapseberg, the strike of the banding is generally almost east-west, and farther north at Menschlief it swings more to the north, while at Guaapseberg the banding largely trends to the north-east and is highly folded in a north-easterly to north-northeasterly direction.

The F_2 folds are frequently not as tightly appressed as in the other areas and there is also the difference in the direction of plunge. A very strong mineral lineation parallel to the plunge of F_2 folds is developed here. F_3 folds are open and asymmetrical (Fig. 23) and are associated with narrow east-west shear zones along which left-lateral movement took place. A small dome-shaped structure occurs north-east of Guaapseberg and is typical of the shape of interference structures between F_2 and F_3 folds seen elsewhere. Pegmatite stringers, as well as lenticular pods of epidote, are again parallel to this direction.

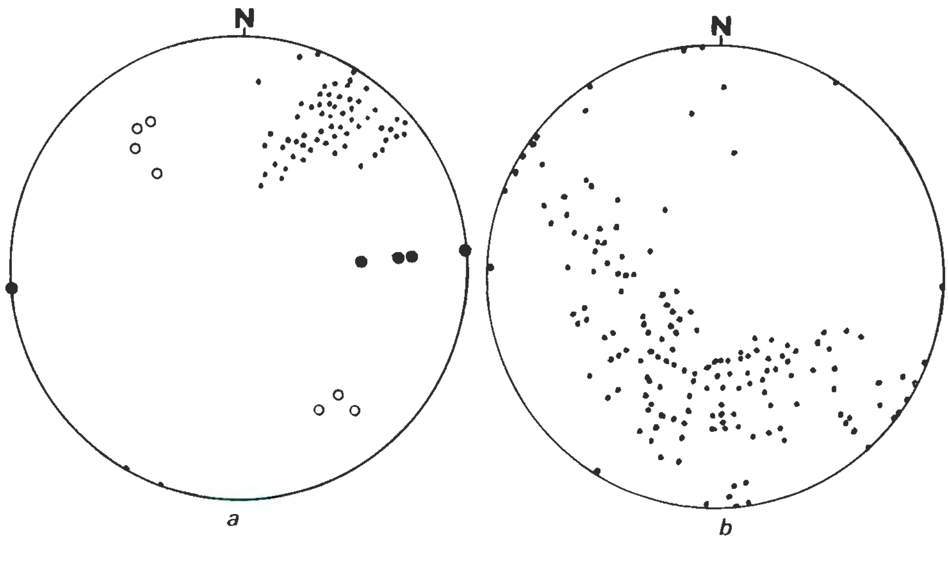


Fig. 22. Equal-area projection of the structural elements at Guaapseberg
(a) Linear elements; l_2, small dots; l_3, large dots; l_4, circles.
(b) Poles to banding and foliation

Fig. 23. Types of F_3 folds in the Guaapseberg area

Strong jointing is apparent in an east-west direction, but this is especially prominent in association with the succeeding episode F_4 folds. The folds of the fourth generation are again mild and in one case were monoclinal in style with the short limb to the east. West-northwesterly shearing is less strongly developed here and is seen only as minor crenulations along planes of slip showing both right and left-lateral movements. Small north-easterly and north-northeasterly trending shear zones are present with pegmatites in places along them and they all show right-lateral movements; this sense of movement for these directions is unusual elsewhere in Namaqualand. The Guaapseberg area is also different from those described above in having the gneisses folded mildly along north-east to north-northeast trends during a late phase of deformation (Fig. 24). Many north-south joints are present and are especially numerous as the faults on either side of the outlier are approached.

A dolerite, presumably of post-Karroo age, traverses the inlier in an east-west direction to the north of Guaapseberg.

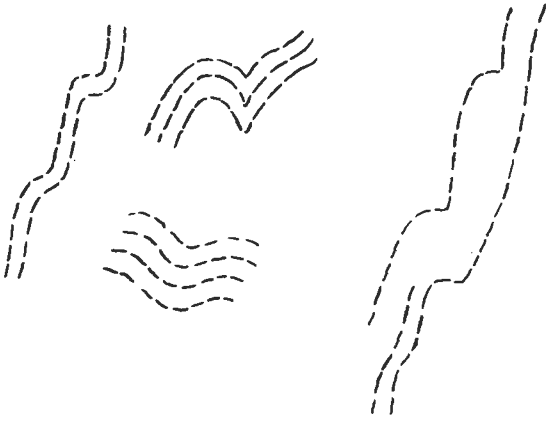


Fig. 24. Types of folds of a late phase of deformation at Guaapseberg

4. Soutfonteinkop

F_1 folds similar to those described for the Banke area were again seen in a number of places on Soutfonteinkop, but in some of the rock types here the F_2 folds are especially well preserved (Fig. 25). The style of the closure in the hill as seen on the map is typically that of a hinge zone of the small-scale F_2 folds seen in many localities on and around the hill. F_2 folds and lineations generally plunge at moderate angles to the north-west and their axial planes and the foliation largely dip in the same direction (Fig. 26). Strong lineation in the form of elongate clusters and streaky aggregates of biotite is distinct in the more mafic types of rocks, but poorly developed in the others. The axial trace of the fold on Soutfonteinkop can be followed to the hill to the west along the line of mafic rocks and it, as well as the lineations, is curved to the north and eventually to the north-northeast by subsequent deformation (F_3).

Small-scale F_3 folds are not pronounced and appear mainly as mild curvature of the foliation between widely-spaced planes of slip along which pegmatites frequently appear (Fig. 27). All subsequent deformations are like those described above. Numerous dolerites are emplaced along north-northwest fractures and these have been fractured since their emplacement.

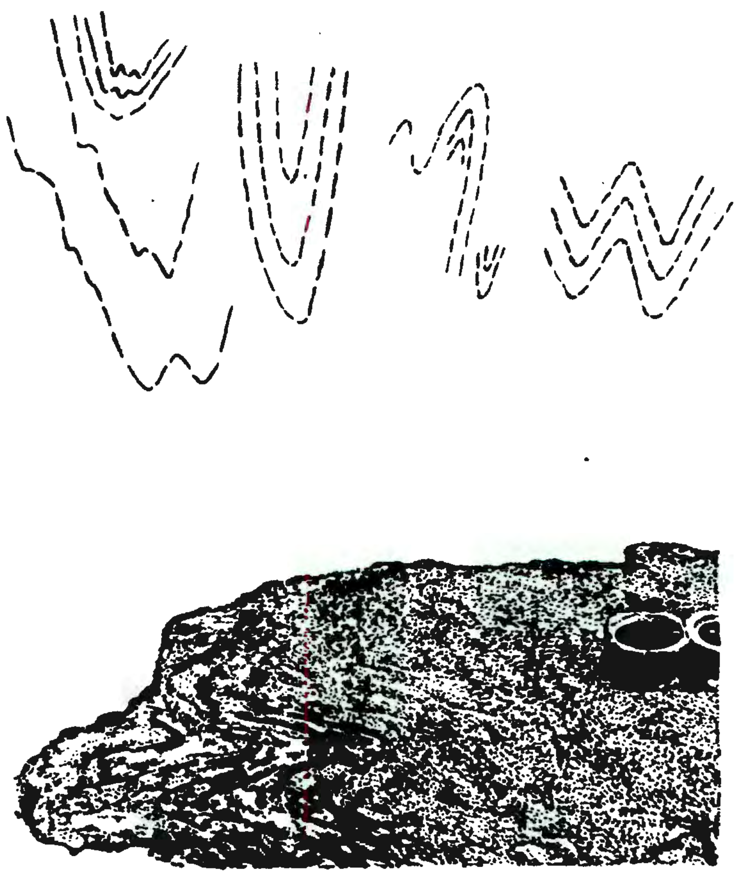


Fig. 25. Examples of F_2 folds on Soutfonteinkop

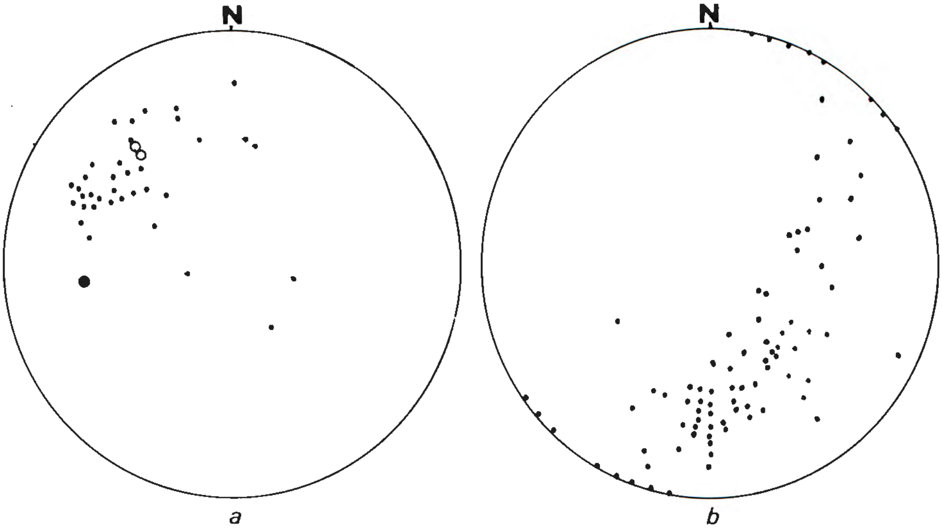


Fig. 26. Equal-area projection of the structural elements at Soutfonteinkop
(a) Linear elements; l_2, small dots; l_3, large dots; l_4, circles.
(b) Poles to banding and foliation

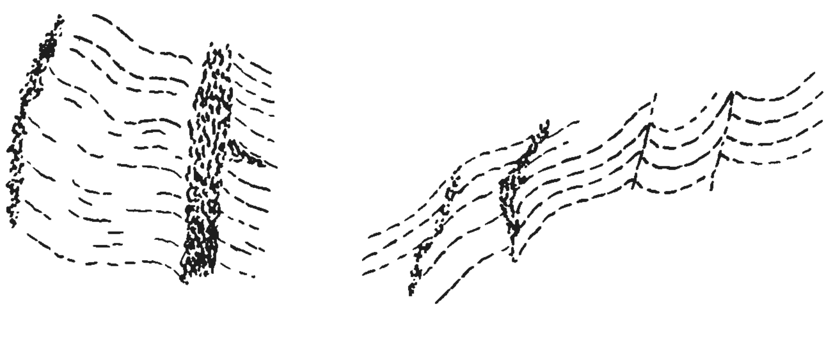


Fig. 27. Structures resulting from deformation during F_3 on Soutfonteinkop

5. Summary of structures in the eastern part of the area

In conclusion the deformation of the gneisses of the areas examined in greater detail is as follows:

(a) F_1 - Tight isoclinal folds with axial planes parallel to the prevalent banding.

(b) F_2 - Isoclinal to close folding; plunge of folds generally to the north-west, but is variable; attitude of the axial planes varies from region to region. Strong accompanying lineation in most places.

(c) F_3 - Open asymmetrical folds, often monoclinal with steep limb to the south; consistent axial planar trend of N85°E. Prominent refoliation in zones where lineation is also developed.

(d) F_4 - Mild folds dying out along strike; consistent axial planar trend of N35°W. Monoclinal folds common and prominent refoliation along narrow zones in the north; strong jointing in the south. Lineation in F_4 rare.

(e) Shearing in three directions giving rise to foliation crenulations and in some places to mild folding:

- (i) N65°W (earliest). Prominent in the north, less strongly developed in the south.
- (ii) N65°E.
- (iii) N30°E (latest). More prominent in the south.

(f) Faults. Prominent north-south fracturing and jointing over the whole of the area.

C. THE FIRST EVENT

1. The first episode of deformation

The evidence for the existence of an early phase of deformation can be seen all over the area in small isoclinal folds with sharp hinge zones and related penetrative axial plane schistosity (s_1) parallel to the lithologic layering, in the presence of intrafolial folds and in the repetition of similar lithologic sequences which have been deformed during the succeeding phase of deformation. The first episode is the oldest deformation recognised and it is not implied that earlier phases of deformation did not take place.

One of the most prominent and common structural features of the area is the lithological layering displayed by alternating dark and light coloured or coarse and fine-grained bands and streaks. The dominant foliation and banding are also expressed by the dimensional orientation of flaky and platy minerals, quartz-felspar augen and elongated mafic pods and these serve as reference planes in deciphering subsequent phases of deformation.

Small folds with sharp hinge zones (Plate XII) are frequently seen in the banded rocks over the whole of the area and lie with their limbs parallel to the banding or planes of discordance. The folds show thickening in the hinge zones and they have tapering limbs which are progressively dismembered away from the hinges in lines of isolated lenticles.

Lineation belonging to the first deformational episode could rarely be identified with reasonable certainty and this apparent lack of l_1 can possibly be attributed to the strong deformation during F_2 and the ensuing strong recrystallisation during high-grade metamorphism. However, some undoubted l_1 lineations, for the most part rather vaguely expressed by elongated aggregates of biotite and more infrequently by the elongation of quartz grains, are found in the hinge zones of F_2 folds where s_2 has not been strongly developed, but elsewhere along the long limbs of folds of the second generation, the planar elements of F_1 and F_2 are essentially parallel and a distinction is hardly ever possible.

Transposition which resulted in the banding also gave rise to the formation of intrafolial folds (Turner and Weiss, 1963, p.116) which, whenever the outcrops allow examination in more than one plane, always appear to be related to F_1 deformation, but as pointed out by Park (1969, p.334), uncertainty of correlation of these folds may arise in areas of polyphase deformation.

The repetition of similar lithologic sequences folded by the succeeding phase of folding (F_2), can also be ascribed to the first episode of deformation. An excellent example of such circumstances can be seen in the fold south-east of Inkruip (3018AA)

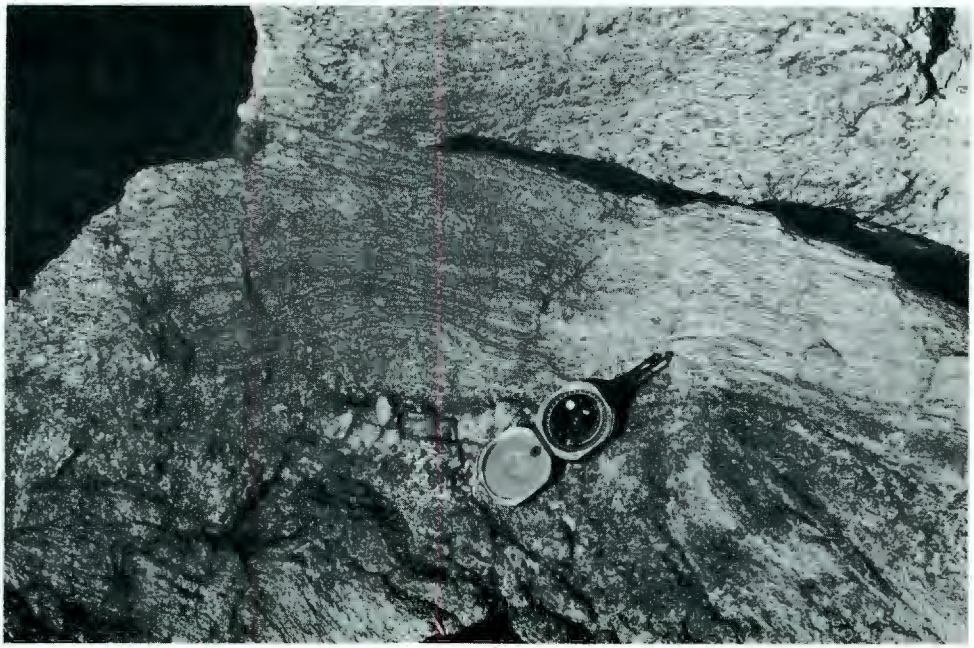


Plate XII. Tight folds with sharp hinge zones of the first generation are commonly seen in banded rocks in the eastern part of the area. Here they are mildly curved by folds of the fourth episode

where an F_1 fold hinge can also still be identified. The difficulties experienced in trying to determine a more detailed stratigraphic sequence for the paragneisses applicable over an area of more than just a few hundred km^2 are probably mostly referable to this episode.

The bands of mafic rocks occurring within the Nababeep gneiss, as described above, were produced by isoclinal folding and narrow synclinal zones of the overlying mafic rocks occur pinched into the gneiss. If any angular discordance existed, these were obliterated during F_1 deformation and the sedimentary structures, such as ripplemarks and cross-bedding described as occurring in the quartzites of areas to the north and east (De Villiers and Söhnge, 1959; von Backström, 1964), were likewise erased.

In a discussion on the first folding in the Moine rocks of Scotland, Ramsay (1963, p.162-167) visualised intense shear deformation producing the earliest folds and leading to the obliteration of all angular discordances in and between the basement and the cover rocks. Sheets of Lewisian basement in the Moine rocks most likely originated as folds or thrusts at a very early stage in the deformational history. However, there appears to be much disagreement on the nature of the earliest structures deforming the Moinian (Johnson, 1965, p.94-101) and with more detailed investigation in Namaqualand, interbanding of the basal gneisses and overlying paragneisses may prove to be due to allochthonous thrust slices similar to those suggested by several authors for the repetition of basement and cover rocks of the Lewisian and Moinian. In the present area no evidence for thrusting during the first episode of deformation was found and it is thought that the repetition was brought about by isoclinal folding. It is uncertain whether mylonites would still be recognised if their generation preceeded strong recrystallisation although exhaustive search and careful mapping might reveal zones of rocks similar to the streaky granulite interpreted as recrystallised mylonite by Fleuty (1961) and may be encountered associated with tapering lithological units other than those which can be related to subsequent deformation.

The presence of sedimentary structures to the north indicates that deformation is less intense there than in the present area and the possibility that the earliest folds open out and disappear in that direction in a similar manner to those described by Ramsay and Spring (1963), cannot be ruled out.

Large F_1 folds are only infrequently seen and Bowes (1969, p.18) ascribes the rarity of the early folds to tectonic disruption during formation of the dominant foliation. There are numerous examples of smaller folds of similar geometry which have been demonstrably distorted during the F_2 episode, and they therefore belong to this first generation of folds. Their hinge lines are found plunging in all possible directions and their axial planes vary in attitude from horizontal to vertical. In contrast to the eastern regions, in the area to the west of the escarpment where much later shearing has taken place and where F_2 folds are tightly appressed, folds of the F_1 generation can only infrequently be identified but small aplitic or pegmatitic veins deformed by typical F_2 folds have been found.

F_1 folds are only important as far as the foliation and banding are concerned and have had less effect on the present distribution of the different lithologies than subsequent phases of deformation. F_1 folds are not recognised by the geologists of the O'okiep copper mining district and as the geological sequence is consistent over most of their area, the possible presence of F_1 folds does not affect the search for ore. Söhnge (1950, p.931) refers to the banding as original stratification while Van Zyl (1967, p.10) records that the foliation appears to coincide with the original sedimentary bedding planes. However, it is interesting to note that Rogers and Du Toit (1908, p.19) already recorded the existence of "isoclinal type of folding" in the large "syncline" (F_2?) west of Prieska.

Very little could be determined about the metamorphism during the first deformational episode and this can be ascribed to complete recrystallisation during the later, high-grade metamorphic cycle. In some thin sections lenticular quartz aggregates with dimensional orientation at an angle to the foliation identified as s_2 can probably only indicate deformation prior to F_2. In a few of the granulites not containing separate crystals or flakes of hornblende or biotite, these minerals were found as small rounded grains or flakes in hypersthene porphyroblasts.

The streaky augen-gneiss found in the south-westerly part of the area (3018CA and CC) was emplaced in the metasediments during a very early stage of the geological history of the gneisses as it was clearly deformed together with the paragneisses during F_2 deformation. By virtue of its nature, structural elements are not easily determined in this gneiss and it could not be established whether the rocks were emplaced prior to, during or after the F_1 phase of deformation.

2. The second episode of deformation

Folds deforming F_1 folds and the dominant foliations are mostly isoclinal with rounded hinge zones (Fig. 28) (Plate XIII) and are clearly outlined as large closures on the map in regions where the axial planes of F_2 folds are steeply inclined or the folds are upright. In large parts of the area these folds are recumbent or gently reclining and then their existence is not so clearly defined by the disposition of the different lithological units.

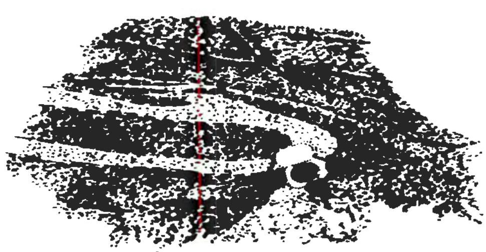


Fig. 28. Typical F_2 fold on Tweefontein

Plate XIII. F_2 fold on north-western side of Tweefontein structure

F_2 folds are usually symmetrical, but less tight, asymmetric folds do occur in some localities. Along the steep limbs of tight folds, smaller open and symmetrical folds having a common axial-plane foliation with the isoclinal folds are frequently found.

The present attitude of the F_2 structural elements is mainly dependent on their situation on the large structures formed later and the configuration of the lithologic units in the area is largely controlled by the F_2 isoclinal folds and their disposition after deformation by the subsequent episode of folding.

Some of the variation in the attitude of l_2 is possibly due to the superimposition of the s_2 foliation on a deformed surface, but the disposition of the lineation is largely or entirely due to the later deformation. In places the folding is intense and the hinge zones have strongly developed axial-planar schistosity expressed as secondary foliation and even banding with concomitant destruction of the original lithologic layering. Although the folds are isoclinal in general, rupturing and shearing along the axial-plane foliation often accompanies folding, but much less tectonic attenuation of the lithologic units along the limbs of these folds is evident compared to those formed during the preceeding F_1 phase of deformation.

As the long limbs of F_2 isoclinal folds are parallel to the layering and s_1 foliation, s_2 is essentially parallel to s_1 for much of the area and it is only in the hinge zones of F_2 folds that s_2 can be distinguished with absolute certainty; refoliation during F_2 was clearly intense and the foliation measurements over most of the present area represent s_2.

A most useful aspect of the geology of Namaqualand is that, outside of the shear belts related to later deformation, lineation can nearly always be related to minor F_2 folds. This lineation is usually conspicuous and is expressed not only as mineral and mineral aggregate orientation, but also as rodding, mullion and boudin structures.

From the regional survey it has become clear that the original strike of axial planes of the F_2 folds prior to subsequent deformation was north-west or north-northwest with dips to the north-east and with reference to the present surface or horizontal plane, they closed sideways. The original hinge lines probably plunged moderately to fairly steeply northwards.

The present disposition of the F_2 folds is the deciding factor in the division of the area into several domains, except in the most westerly parts where later intense shearing and accompanying folding mask, and in many places obliterate, earlier structures. In the southern part of the area from latitude 31°00'S to the shear belt from Eselsfontein (3018AC) to Platbakkies (3018AD), the axial planes, now varying much in trend, are moderately inclined to steeply dipping and in places the folds are upright. North of the shear belt the axial planes of the folds are gently inclined and they are almost recumbent, but their axial planes again become gradually more steeply inclined and north of the line from Pedros Kloof (3018AA) in the west to Boesmanplaat (3018AB) in the east, the axial planes are much curved by the succeeding phase of deformation resulting in the perfect periclinal structures there. This area is separated by a deep synform stretching from west of Kameelboom (2918CC) to Bodabeep (2918CD) from the regions to the north where the F_2 folds are again recumbent and their hinge lines plunge gently towards the north-east. These conditions for F_2 folds remain constant for the rest of the area to the west, except where their disposition has locally, and along narrow zones, been highly deformed by subsequent folding and shearing.

The only modern structural analysis in an area underlain by Namaqualand gneisses has been carried out by Kröner (1968) in a region to the south-southwest of the present area. Here the transposition foliation (op. cit., p.81) strikes east-northeast and is associated with strong isoclinal folding, the oldest folds recognised both in that area, and at the coast farther west (op. cit., p.93-101). The isoclinal folds are described as strongly inclined to almost recumbent and plunge gently to the south-west or south-southwest in places. Jansen (1960) records isoclinal folds only as indicated by uniform dip and strike, but from the description of the fold near Bitterfontein (op. cit., p.62) and the repetition of similar lithologies in the sequence there (p.29), it is clear that these folds exist there and that they trend east-northeast. Farther east and to the south-east of the present area, Pike (1959, p.16) records "tightly folded pitching structures" where the metaquartzites deviate locally from the normal east-northeast strike.

(a) Structural domains

In the south-western part of the present area (sheet 3018CC), the trend of the axial traces of the F_2 folds is also east-northeast, but they have been much deformed by the succeeding phase of folding. However, the prevalent l_2 lineation and minor F_2 folds there indicate that the large folds plunge at 30 to 40 degrees to the north-west (Fig. 27).

The closure seen on Soutfonteinkop is of the F_2 generation, but both to the south-west and to the north-west, the trend of F_2 folds as marked by the repetition of similar lithologic types, is seen to swing sharply (almost through 180 degrees on Louws Cyfer) due to subsequent deformation. Where the trend of the axial traces of folds is east-west, the foliation s_2 dips fairly steeply to the north, a feature which is noticeable in the hills on the farm Bitterfontein and south-east of Soutfonteinkop. To the east the metaquartzites paralleling s_2 swing slightly more to the north-east and disappear under the Nama sediments there. At the inliers farther east on Menschlief and Guaapseberg they reappear and at the latter locality, where a closure is seen, minor F_2 folds and l_2 are observed to plunge to the north-northeast at angles varying from 15 to 30 degrees and even steeper (Fig. 23). To the north-east of Guaapseberg a small periclinal dome is formed by the F_2 antiform refolded during the subsequent deformation. The north-easterly trend persists to the eastern boundary of the present area there, but at Langdam and on Uitspanberg the large folds as shown by the closures on the map, plunge northwards at moderate angles. The trace of the axial plan of the fold to the north-northwest, and onto sheet 3018CA where, at Kliphoek, the trend of the fold, with foliation s_2 dipping at 60 degrees to the north, is parallel to the large west-northwest shear belt across the area just to the north. Along this shear belt (to be described later), the earlier folds have been dragged into parallelism with the shear belt over quite a width of country as can be seen in the synoptic diagrams of that part of the area (Fig. 4), but to the south, the l_2 lineations plunge in various directions in the s_2 foliation planes.

The effects of later east-southeast shearing tend to diminish westwards and north of Draaihoek (3018CB) a closure plunging northwards is again evident. Farther north in the trough of a north-northwesterly trending synform the circular outcrop of mafic rocks is again the result of a large fold of the F_2 generation being involved in later deformation which was described earlier.

A good example of a recumbent F_2 fold occurs in the hills west of the Swartdoring River on the farm Zee Kloof farther to the north (Fig. 29) and has a periclinal structure similar to that at Witplaat on its northern limb. With minor variations, the trend of F_2 folds from south of the east-southeast shear zone to the northern edge of sheet 3018C remains fairly constantly north-west. Thus these folds, having an almost east-west trend in the south, have swung round, rotated by subsequent deformation through more than 90 degrees to become north-west, but their plunges have remained fairly constant at moderate angles to the north-northwest or north, except in the south-eastern part of the area where these folds plunge to the north-northeast.

Farther north on sheet 3018A, the same conditions prevail on the western boundary of the area mapped, but north of Remhoogte, the traces of F folds are highly curved due to subsequent deformation. The largest and best example is marked by the ridges on which Slagieskop beacon stands: the traces of the F_2 folds follow the line of quartzo-felspathic rocks from Matjes Kloof in the east where these rocks first appear in the keel of an F_2 trough and continue to the west, swinging through 180 degrees round Slagieskop towards Roode Kloof Hoek. Around Slagieskop, it is clear that these rocks do not lie only in a single fold, but the increase in outcrop width is brought about by a series of F_2 folds curved around the structures there and against the major shear zone to the north. Unfortunately the leptite, by virtue of its granulose nature, mostly yields little structural data, but in

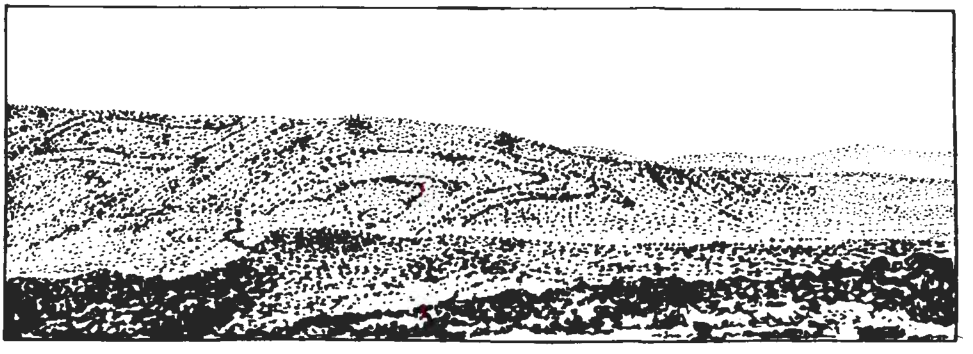


Fig. 29. Large scale recumbent F_2 folds in the hills on Zee Kloof deformed by later F_3 folding

this fold it is clear that the axial planes of the F_2 folds are near vertical to the south-east of Slagieskop beacon, but north of there the dip of the axial planes is westerly and on the northern limb of the large fold, they tend to dip more gently to the north.

Similar folded F_2 folds occur in the whole of the southern part of sheet 3018A and south of the Eselsfontein-Platbakkies shear belt, and the traces of these folds are marked by the sinuous contacts shown on the map. Similarly, the direction and amount of plunge of the folds are much disturbed, as indicated on the map of that region by the lineations, most of which belong to F_2 deformation.

To the north of the Eselsfontein-Platbakkies shear belt the F_2 folds have been less disturbed by later deformation and their axial planes are recumbent to gently inclined while the minor folds and l_2 lineations indicate that these folds now plunge at shallow angles mainly to the north-east. The repetition of similar lithological types can mainly be related to F_2 folds which are also responsible for the closure east of De Riet (3918AB) and the earlier of the two folds responsible for the brachy-anticline of Couragie Fontein (3018AA, AB). Smaller F_2 folds can be seen folded around the hinge zone of an F_3 antiform east of Olyven Fontein (3018AA). North of the line from Modder Fontein (3018AA) in the west to Vaal Puts (3018AB) in the east, the axial planes dip more steeply to the north-east as these folds become more involved in subsequent deformation. From here and up to the mafic belt from west of Kameelboom (2917DD) to Bodabeep (2918CD) F_2 folds are again highly inclined and much contorted about axes of the later generation of folds. A well-defined closure of a large F_2 fold plunging to the north-east can be seen to the north of Rooi Doorn Kloof (3018AA), while periclinal structures are seen west of Rooifontein beacon, between Paarde Hoek and Inkruip and on sheet 2918CD at Tweefontein.

To the north of the mafic belt mentioned above, the F_2 folds are nearly recumbent as shown by the structure between Eendoorn and Silver Fontein and their hinge lines can be seen to plunge gently to the east-northeast, while their axial planes have been gently curved by later, almost parallel-trending folds. South of Platjes Fontein (2918CC) a fold typical of the shape and style of F_2 deformation occurs. It is formed by spindle-shaped mafic phacoids in the acid gneiss which lie across the band defining the fold, similar to the structure illustrated by King and Rast (1956, p.190, fig.2c). The elongated phacoids plunge gently to the east in the direction of the axis of the fold.

To the west of the Silver Fontein structure and south of Mesklip and Koornhuis (2917DD and DC), mafic rocks representing the subsequently deformed keel of an F_2 fold mark the position of folded folds there, and farther west an elongated eye-structure is formed by the superimposition of F_3 folds on those of the F_2

generation.

Large F_2 folds are sometimes seen in the sides of hills, but because of the penetrative foliation, these folds are not recognisable in the biotite gneisses. The best example of large isoclinal F_2 folds is displayed in the quartzites at Koornhuis beacon hill where the lineation and hinge lines of the minor folds plunge at approximately 25 degrees to the north-east (Fig. 1). Elsewhere in these regions the mafic rocks lie along the traces of F_2 folds and a fairly regular lineation here indicates that the folds plunge fairly gently towards the north-east.

In the Komaggas area later shearing and deformation mask much of the earlier folding, but the strong l_2 lineations reveal that the trend of the F_2 folds generally swings from a north-easterly direction of plunge to north-northeast farther west as the escarpment is approached. The same feature is seen in the region to the north-west of Komaggas. In the areas covered by sheets 2917AB, AD and CB, the north-easterly plunge direction of the folds changes gradually on proceeding west and locally, due to later deformation, becomes north-northeast. The plunge as indicated by the lineation and minor fold hinges, however, is generally to the north-east at a fairly gentle angle, but at Dikgat along the Buffels River, the recumbent F_2 folds were much deformed by strong shearing during a later episode and now plunge at low angles in a direction from just east of north to north-east (Fig. 30).

In the northern part of the western regions most of the earlier folds plunge, in sympathy with later deformation, in a north-northeasterly direction, but at Chabiesies (2917AB) several minor F_2 folds were again found plunging to the north-east (Fig. 31).

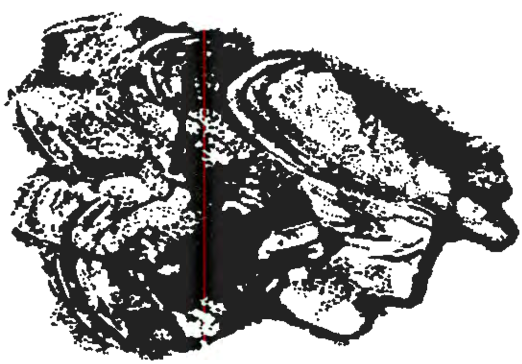


Fig. 30. F_2 folds in metaquartzite, Roodevlei trigonometrical beacon

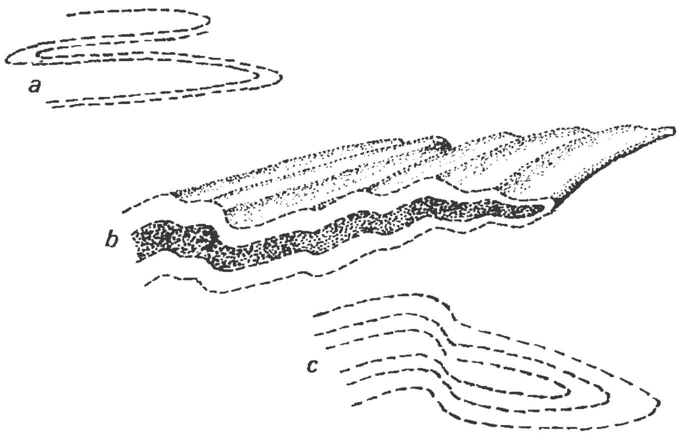


Fig. 31. Types of F_2 folds in the Chabiesies area;
(a) undeformed,
(b) deformed in a north-easterly direction and mildly refolded along a north-south trend and
(c) refolded in a north-northeasterly direction

The general swing of the lithologic layering and traces of earlier folds from north-east in the eastern regions to north-northeast in the west is due to large-scale lateral movement in the area west of the escarpment during subsequent deformation discussed later.

(b) Regional setting

Judging by the descriptions of the geological structures to the north and east of the present area, isoclinal folding is widespread and forms a regular pattern in all area of Namaqualand and Bushmanland where the metasediments and metavolcanics with lithologies similar to the rocks of Kheis age are exposed. As in the case of the present area, the general trend of the isoclinal folds is north-west to north-northwest, but shows much variation in a wide zone along which periclinal cross-structures resulted from later deformation.

Some 380 km east of the present area, to the west of Prieska, the isoclinal folds strike north-northwest (Rogers and du Toit, 1908 and personal observation) except where mildly deflected by later folding. This strike is borne out by the continuous range of hills composed of Kaaien quartzite which stretches from beneath a blanket of Karroo rocks in the south to its crossing of the Orange River east of Upington, a distance of 250 km. Along the northern part of this line and towards the west in the Keimoes area, periclinal structures have been formed and it is clear that the domain of large-scale later deformation has been entered, but the axes of the isoclinal folds generally still plunge to the north-west and axial planes dip from 25 to 70 degrees to the north-east (Von Backström, 1964, p.169).

Farther north in the Riemvasmaak area, just east of the south-east corner of South West Africa and north of the Orange River, von Backström (1967, p.48) described the isoclinal folds as having a similar disposition in trending north-west with northerly dipping axial planes, while to the west down the Orange River valley between Onseepkans and the Richtersveld, it appears that the effects of cross-folding are still pronounced east of longitude 18°15'E (Von Backström and de Villiers, in the press), but to the west the isoclinal folds strike east-west into the Richtersveld (De Villiers and Söhnge, 1959, p.198-199) and eventually their trend swings again to the north-west. Here there is an apparently important difference in that the axial planes of the isoclinal folds dip to the south-west. This feature was observed personally in the valley where the Bak River cuts through the quartzites forming the Rosyntjiesbos Mountains. In this locality the oldest folds observed in the quartzites are isoclinal in style and have axial planes dippling at 60 degrees to the south, while the associated strongly developed rodding in the quartzites indicates that the folds plunge at 35 degrees almost due east.

An area to the east of the northern part of the present area, is being investigated by Mr. J.H.W. Ward and he finds that the structural features of that part of the present area are persistent to the east and that the isoclinal folds there are almost recumbent and that their hinge lines and associated lineation plunge gently towards the north-east.

In the O'okiep area, where detailed geological investigation has been carried out in the search for copper deposits, careful studies have been made of the finest details and the structures encountered in that region can also be fitted into the larger framework of the present area. Although Strauss (1941) did not recognise the existence of early isoclinal folds, he described irregularities in the northern limb of the "Springbok dome". Benedict et al. (1964, p.258) referred to "Old" recumbent folds as being tight and approximately isoclinal with easterly trending axial planes and shallow plunges. On the northern side of the "Springbok dome", the axial planes dip to the north, but on the southern side, the dip is to the south. They also listed the reasons why these incongruous folds are not merely drag folds related to the deformation resulting in the "Springbok dome" and a photograph is shown of a style typical of the F_2 generation (op. cit., Fig. 1, Plate XII). It may thus be suggested that, as in the present area, the repetition of similar lithologies in the sequence at O'okiep (op. cit., p.246) is due to isoclinal folding as is the case in the Silver Fontein structure described above, and that there is only one quartzite-schist association as in the present area. It is therefore suggested that, as suspected by some of the geologists there (B. Packham, personal communication), the Springbok schists and quartzites and those of the Ratelpoort 'Stage' are equivalents and perhaps also those of the Wolfram Stage. Furthermore, it is thought that the Upper and Lower Springbok "granulites" are representatives of the same lithological unit and it therefore follows that the Brandberg gneiss can be correlated with the Nababeep gneiss. The Concordia gneiss, although lying in an east-west zone parallel to the major banding in the area, is believed not to form part of the normal paragneiss sequence, but belongs to a later phase when the granites were emplaced. This is also consistent with the views expressed by some of the investigators there (G. Schreuder, personal communication).

(c) Metamorphism (M_2)

Although polyphase metamorphism complicates the history of the Namaqualand gneisses, it has been possible to delineate zones of progressive metamorphism in the area as indicated by the mineral assemblages as shown in folders 1 to 4. The exact positions of the isograds separating the different zones, except in some localities, must at the present stage of knowledge remain rather uncertain until more detailed studies can be carried out.

During F_2 deformation the Namaqualand gneisses were subjected to strong recrystallisation and migmatisation, while the metamorphism reached its peak during or after this phase. Strong mineral lineations and augen developed and in places coarse recrystallisation resulted. The porphyroblastic granite-gneisses with their coarse migmatitic banding (Plate IV) occurring northeast of Komaggas and farther to the east as well as those north of Eselsfontein (3018AC) reached their present aspect during this stage while, at the same time, the augen of the Nababeep gneiss were formed.

There are two indications that the metamorphic episode outlasted F_2 deformation. In the Eselsfontein area, the large porphyroblasts do not show dimensional orientation away from the contacts and Ramsay (1963, p.169) accepted randomly orientated porphyroblasts as indicating continuation of metamorphism and growth of porphyroblasts after cessation of deformation. Secondly, sheets of basic rocks apparently intruded along s_2 foliation planes now have the composition of granulite and were metamorphosed since their emplacement.

The metamorphic zoning is expressed by the mineral assemblages encountered in the metamorphosed pelitic and mafic rocks, but, as pointed out before, it is complicated by subsequent retrogressive metamorphism and by later metamorphism associated with the granitic intrusions in the area now forming the coastal plains. The metamorphic zones as shown on the map parallel the original trend of F_2 folds, but they have been involved in subsequent deformation which must have resulted in deviations in the isograds and are here shown as lines of fairly regular strike. With more detailed investigation, the isograds will no doubt depart from the regular north-northwest strike in many places.

Five zones of differing degrees of metamorphism have been recognised, and with more closely spaced collection of samples, it is almost certain that further subdivision will be possible.

(i) Zone A. Along the coast the pelitic part of the lithological sequence is represented by muscovite-quartz schists. These rocks have been subjected, subsequent to their formation, to intense shearing deformation with attendant retrogressive metamorphism, and minerals like staurolite, garnet and biotite were introduced later probably during the emplacement of younger granites in that part of the area. Since the emplacement of the granites, rejuvenation of shearing farther complicated the picture and it is therefore impossible to ascertain whether quartz and muscovite were the only minerals present in the pelitic rocks after M_2 metamorphism. Also, in that part of the area exposures are not as continuous as farther east.

At Grootmis the pelitic rocks consist only of quartz and muscovite, but there they have been intensely sheared during the later phase of deformation. Farther to the east these rocks are found also to contain biotite, chlorite, plagioclase and even potash felspar, but biotite disappears in the immediate vicinity of the granite east of Grootmis and the rocks contain garnet instead.

Along the base of the Stinkfontein Formation at Nakanas (2917AC) large amounts of staurolite occur in the schists and the large idioblasts consist of cores dense with small inclusions mantled by clear rims possibly indicating further growth at a later stage. It is therefore likely that staurolite enters the assemblage of the M_2 metamorphic zone on the eastern side of the zone as the kyanite isograd is approached.

The mineral assemblages, although confused by later metamorphism, appear to indicate greenschist facies metamorphism and possibly this grades into the lower amphibolite facies towards the east.

(ii) Zone B. East of a north-northwest line from Oograbies West (2917AA) towards the south across the western part of Gemsbokvlei (2917AC) and to the west of Roodevlei beacon (2917CA), kyanite first appears in the pelitic rocks. This mineral was encountered in the inlier of basement below the Stinkfontein Formation at Oograbies West, below the Stinkfontein Formation at Gemsbokvlei, in the rocks on the eastern side of Nakanas and farther east towards the farm Steenbok and the most westerly occurrence along the Buffels River was found at Dikgat. From there kyanite appears in the pelitic assemblages up to and as far as the escarpment. These rocks, apart from kyanite, contain quartz, muscovite, biotite, garnet, plagioclase and usually some staurolite. The same mineral assemblage, but without kyanite, has been found over a much wider area to the north and north-east at Haouseep and Nanassen (2917AB) where staurolite is prominent. In effect then, this zone is most easily recognised by the presence of kyanite, but in its absence the mineral assemblage quartz-muscovite-biotite-garnet-staurolite in the pelitic rocks is indicative of the second zone.

In the north-eastern part of the area no minerals indicative of the grade of metamorphism during M_2 have been found. This is almost certainly due to collection of samples being concentrated along zones of later deformation, but in traversing those regions, rocks obviously containing kyanite or staurolite were not seen.

Kyanite crystals are small in the western part of the area, but increase gradually in size and become more conspicuous towards the east. At the sillimanite-isograd at the foot of the escarpment north-west of Komaggas the kyanite crystals locally attain lengths up to eight cm. In that area a rock containing kyanite, sillimanite and staurolite was collected, but here the staurolite is demonstrably of later generation (Fig. 32) and the occurrence of chlorite enclosing kyanite indicates polyphase metamorphism.

Although the kyanite isograd is shown in folder 4 as a fairly straight line, it would be surprising if that is its actual configuration, as fairly strong folding and shearing in the area on the coastal flats must have resulted in sharp deviations in the line. However, even after a more detailed examination of that region, it would be difficult to place its position more accurately because of lack of exposure, especially along the southerly extension of the line.

The mineral assemblages of the second zone are indicative of the staurolite-almandine subfacies of the almandine-amphibolite facies (Winkler, 1967, p.107-109).

(iii) Zone C. Of all the isograds, the sillimanite isograd is the most conspicuous in the field, especially in the region to the north-west of Komaggas. Along this line garnet is very prominent in a belt some four to five km wide to the east of the isograd and, while sillimanite takes the place of kyanite to the east of the isograd, it also appears to coincide with the westerly limit of the presence of hypersthene. Farther east cordierite

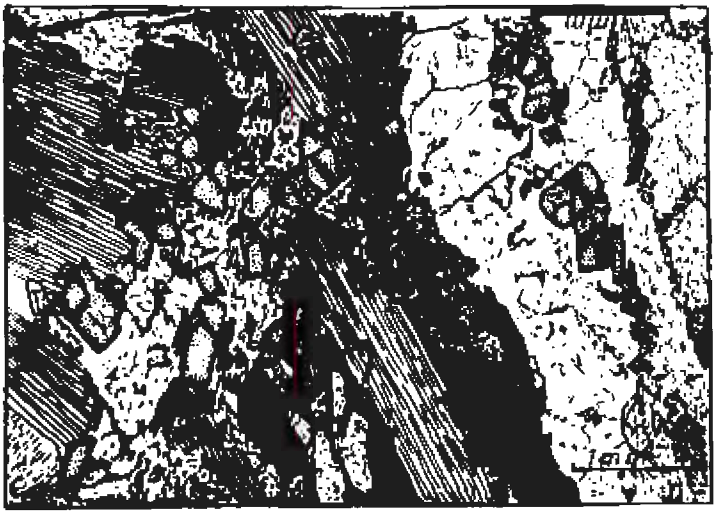


Fig. 32. Staurolite crystals (stippled) across the foliation in a muscovite-biotite schist from Komaggas

is found instead of garnet. Sillimanite was also found to the north as far as Wit Klip Hoogte after which the isograd leaves the confines of the present map. The copious formation of garnet is again seen to the east of the isograd there and the most westerly occurrence of hypersthene was found at Harras in an isolated outcrop surrounded by sand. This mafic rock now has the composition of a bojite.

The most westerly occurrences of cordierite were found in the hills just east of Komaggas where this mineral appears in a gneiss of which the major mafic constituent is orthopyroxene, and to the north-east of Komaggas in a cordierite-sillimanite gneiss.

In zone C both ortho-and clinopyroxenes usually occur in amphibolites, but the two types of pyroxene never appear together in the same rock.

South of Komaggas sillimanite-cordierite gneisses again occur on the farm Kraaifontein (2917DC), therefore the sillimanite isograd passes west of this locality and out of the area of the present map. In the far south Jansen (1960) found sillimanite in the Bitterfontein area, while kyanite appears in the metaquartzites in several localities to the west and south-west of the sillimanite occurrences (op. cit., p.14). The sillimanite at Rietfontein in the west can, according to Jansen (op. cit., p.30) be attributed to the intrusive complex at Kogelfontein. The sillimanite isograd can thus be extended southwards from the position where it leaves the present area in a south-southeasterly direction and west of the southern part of the present area, perhaps passing through the south-westerly corner and farther south some 20 km west of the township of Bitterfontein. Within this zone Jansen found the sillimanite-cordierite gneisses and encountered one example of a hypersthene-cordierite gneiss, but no rocks of the composition of a granulite are described.

To the north of the present area sillimanite is still found south of the Orange River to the east of Vioolsdrif and between Steinkopf and Vioolsdrif (De Jager, 1963), but to the north-west of the latter occurrence, andalusite appears (J.H.W. Ward, personal communication). Von Backström and de Villiers (in the press) found sillimanite and cordierite gneisses in the valley of the Orange River, but farther south-west, and east of the Neint Nababeep Plateau, sillimanite-andalusite-hornblende rocks occur. This association possibly indicates that the sillimanite isograd passes through that locality and the appearance of andalusite possibly signifies that the triple point andalusite-staurolite-sillimanite (Althaus, 1967) lies between there and the present area, but its presence may also be due to a later phase of metamorphism.

The sillimanite occurrences east of Stinkfontein in the Richtersveld (De Villiers and Söhnge, 1959, p.44) appear to have formed in a north-northeast shear zone of a much later stage of deformation and are probably associated with the intrusion of the Richtersveld granite.

This third zone is intermediate between the amphibolite and granulite facies assemblages. Wynne-Edwards and Hay (1963) found that cordierite is a stable phase in high-grade regional metamorphism and that its presence is dependent upon the bulk composition of the rocks so that in rocks with a higher ratio of CaO and FeO relative to MgO, garnet is formed instead. They state that cordierite-biotite and cordierite-garnet-biotite gneisses "appear to occupy a field intermediate between upper almandine amphibolite and pyroxene granulite facies" (op. cit., p.453).

Cordierite-sillimanite gneisses are widespread even to the east into the area where the assemblages indicate granulite-facies metamorphism, but much of the cordierite is demonstrably of a later generation. The same applies to the appearance of potash felspar in these mineral assemblages and there seems to be no analogy between the presence of potash felspar in the cordierite-sillimanite gneisses and the zoning of M_2 metamorphism. However, in this zone garnet is not usually found in association with cordierite and sillimanite in the same rock except in the south-western corner of the present area, while the assemblage cordierite-sillimanite-garnet is fairly common in the eastern part of the area.

(iv) Zone D. The assemblages found in zone C are repeated in the eastern regions, but with the important difference that clino- and orthopyroxenes now occur together in the same rock. The isograd separating zones C and D is not at all apparent in the field and was only discovered during examination of the thin sections when the fieldwork had been completed. The mineral assemblages as listed with the descriptions of the pyroxene granulites clearly indicate metamorphism of the granulite facies and as in the case of the charnockite series of Madras (Turner, 1968, p.333-334), the granulites here are free of garnet.

As the westerly limit of the granulites is not obvious in the field, its position on the map (folder 4) is rather uncertain, but rocks containing both ortho- and clinopyroxene occur outside the present area to the north of sheet 2918CC and the most westerly occurrence found during the survey is situated in the south-eastern corner of sheet 2917DC. In the eastern regions granulites are of frequent occurrence except for the south-western part of the area including almost the whole of sheet 3018CC. To the south of the present area, it is thus not surprising that Jansen (1960) did not find any rocks containing both clino- and orthopyroxene, while Brink (1950) farther to the east, described a number of pyroxene granulites.

Sillimanite-cordierite-garnet gneisses are commonly encountered in zone D as well as in the area to the south (Brink, 1950, p.136-141). Hapuarachchi (1968) described cordierite-bearing rocks of south-western Ceylon as occurring in a cordierite-granulite subfacies and where the association garnet-biotite becomes unstable in a changed metamorphic environment, garnet reacts with biotite to produce cordierite. In the present area it is thought that the presence of much of the cordierite is indicative of the effects of a later cycle of metamorphism.

There can be no doubt that most of the sillimanite was formed during this phase of metamorphism and the mineral is seen under the microscope as trains of small crystals deformed by subsequent deformation when a second generation of sillimanite was formed (Figs. 33 and 37).

(v) Zone E. Winkler (1967, p.134) listed a clinopyroxene-almandine-granulite subfacies which De Waard (1965, p.186) suggested. Buddington (1966, p.334) believed that De Waard is justified in designating the garnet-clinopyroxene-plagioclase assemblage as indicative of high pressure and temperature in the granulite facies.

Rocks with similar assemblages have been described as garnet granulites above. The garnet coronas separating the plagioclase from pyroxene in most, but not all the rocks, may indicate disequilibrium. In one specimen collected, all clinopyroxene has disappeared and the rock now consists essentially of plagioclase

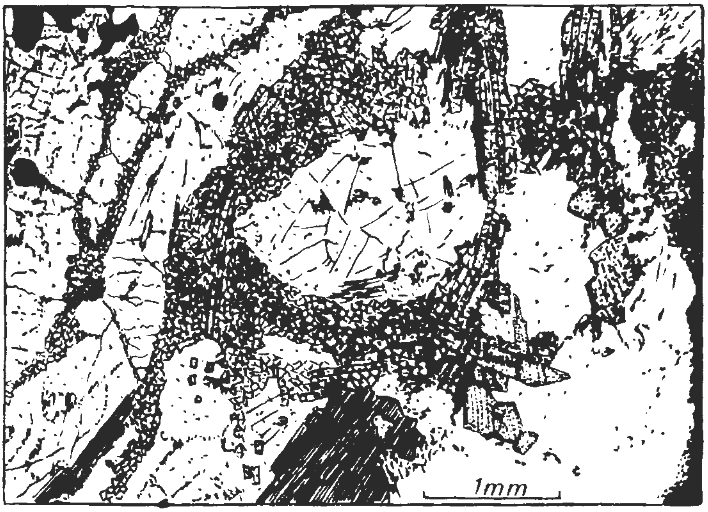


Fig. 33. Trains of sillimanite crystals deformed during the third episode of deformation

and garnet with the distinctive colour always displayed by garnet in these rocks and the rock also has the corresponding granulite texture. These rocks occur south of Springbok in an area on the higher metamorphic side of the granulite-facies isograd. The assemblage therefore appears to indicate the highest grade of metamorphism encountered in the gneisses of Namaqualand.

These deductions would probably have been unimpeachable had it not been for sphene featuring prominently in the garnet granulites. Turner (1968, p.325) has taken the disappearance of sphene from amphibolites as indicating transition from the amphibolite to the granulite facies. Also similar-looking garnets, determined as Ca-garnets and occuring in a corresponding mineral assemblage, are described for the Swakopmund area in South West Africa (Nash, 1971) where a lower metamorphic grade prevails and where it is though that the garnet is formed at the expense of clinopyroxene by oxidation as described by Huckenholz (1969).

However, Hapuarachchi (1967, p.29-30) listed sphene as one of the minerals occurring with the calc-granulites and calc-gneisses signifying a lower grade metamorphism and ascribes its presence to subsequent retrogressive metamorphism. It is most likely that the sphene in the garnet granulites is of later generation as it can be proved that this mineral formed, resulting in expansion cracks, in a rock in zone E and was sheared during a deformation subsequent to M_2 metamorphism. The formation of sphene from other titanium minerals probably happened at the time when the Concordia granites were emplaced. It may be mentioned that Winkler (1967, p.143) listed sphene as one of the accessory titanium minerals present in eclogite, but does not mention its occurrence with granulites.

When the mineral assemblages of the different zones in the present area are compared with the tentative PT diagram prepared by Hietanen (1967, fig. 1), it appears that the metamorphism is similar to that of the Idahoan type but for the absence of andalusite, indicating progressive metamorphism at a lower pressure than that of the triple point. It would also seem that the curve flattens towards the higher degree of metamorphism so that cordierite enters the mineral assemblage before the granulite facies is reached.

It has already been shown that the metamorphic zones can be extended both to the south and to the north of the present area, but from the work elsewhere the indications are that these zones can be extended further and the picture of an important metamorphic episode of tremendous dimensions unfolds.

In the Keimoes area von Backström (1964, p.159-160) distinguished five metamorphic zones: chlorite, biotite, almandine, staurolite and sillimanite. The rocks of charnockitic composition are not taken into account in the zoning nor is retrogressive metamorphism, so prominent in the present area, considered. On the map accompanying his unpublished thesis, von Backström (1961) showed zones of varying metamorphic grade parallel to the trend of major fold axes and the zones appear to indicate composition of the rocks rather than metamorphic zoning, unless they have been folded since metamorphism. However, rocks taken to represent the granulite facies in the present area are also described as occurring in that area. From the distribution of these rocks and the amphibolites which occur in the north-eastern part of the map of the Keimoes area, it may be suggested that there is an increase in grade of metamorphism from the north-east to the south-west across that area.

Rogers and du Toit(1908, p.12) recorded the increase of metamorphism from the north-east to the south-west in the area west of Prieska. The hornblendic rocks in the east can be recognised as altered basic amygdaloidal lavas which become transformed to granulites towards the south-west, and the presence of garnet, staurolite, kyanite, sillimanite and cordierite is recorded.

The grade of metamorphism increases from west to east in Namaqualand and from the north-east to south-west in the eastern Bushmanland, and a thermal structure of considerable magnitude, probably in the form of a simple anticline with an axis trending to the north-west,much as envisaged for the Scottish Highlands by Kennedy (1948), is apparent.

Van Zijl (1970), in conducting deep electrical investigations to determine the electrical properties of the crust and upper mantle, has found a high crustal transverse resistance of the Namaqualand gneisses between Kakamas and Springbok. He ascribed the high degree of metamorphism as indicated by the electrical resistance to a second episode of metamorphism which took place about 1,000 My ago. From the present work it appears clear that the granulite facies metamorphism as indicated by the high crustal resistance, is associated with an earlier metamorphism than the isotopic rejuvenation of the 1,000 My episode.

(d) The age of the F_2 deformation

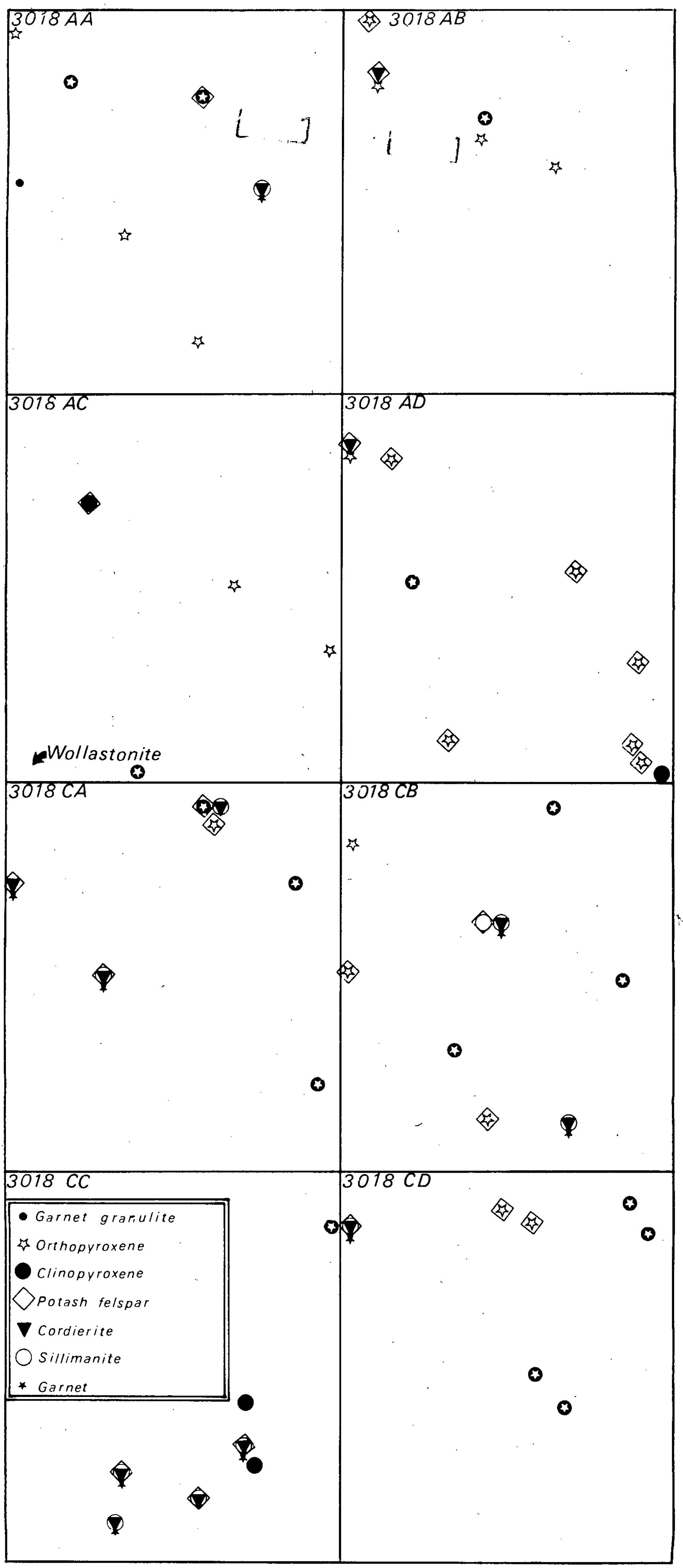
Mr. J.H.W. Ward (personal communication) has found that the grey gneissic or Vioolsdrif granite to the north of the present area, dated as $1,850 \pm 40$ My, was emplaced after the F_2 episode. This useful information, although based on only one age determination and therefore rather tenuous, indicates that the F_2 deformation took place prior to that date.

3. Shear zones and tectonic slides

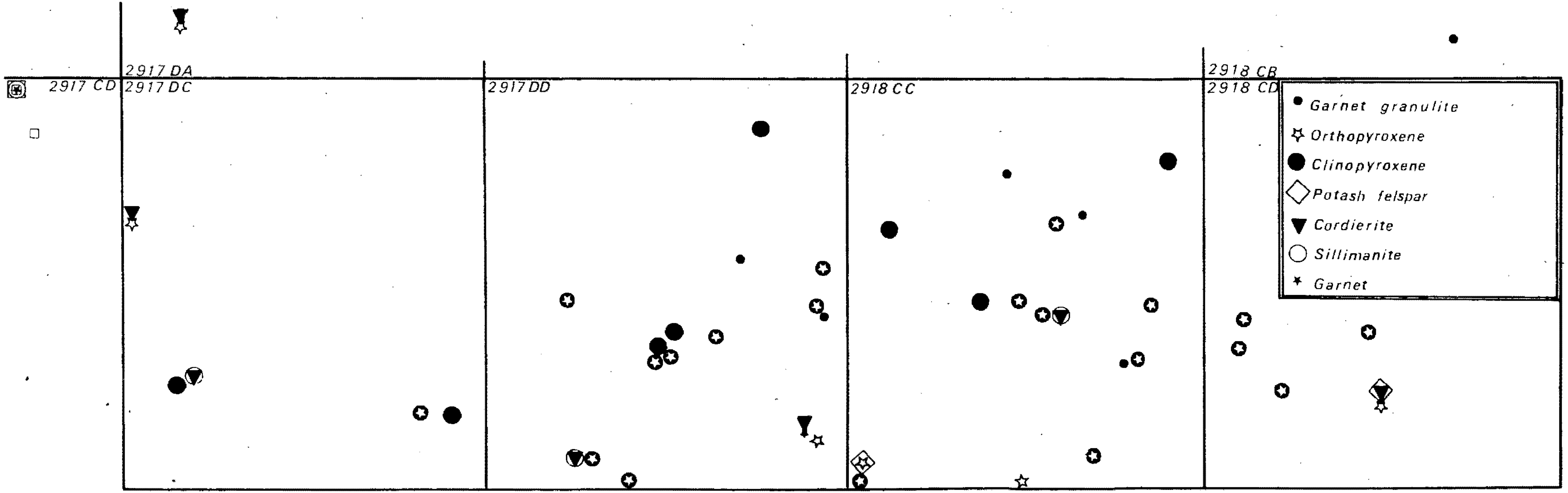
The Namaqualand gneisses have been subjected to shear deformation at various stages during their geological history and large-scale shear zones in at least five different directions have been recorded in different parts of the area. It is especially near the coast where the region is transected by numerous zones along which transcurrent movements have taken place and must be above all, the area for the study of this phenomenon. Although most shear zones have certain features distinguishing them from others of different strike direction and phases of deformation, they have many aspects in common and in order to obviate unnecessary repetition, a general description is given here.

The large shear zones described by Clough (Peach, et al., 1907, p.148-154, 165-170) as occurring in the Lewisian of the Scottish Highlands have been re-investigated by a number of other geologists and not only are field descriptions given (c.f. Sutton and Watson, 1951, 1962; Sturt, 1961; Bhattacharjee, 1968), but also investigations into the mechanisms involved have been carried out (e.g. Ramsay and Graham, 1970) and their position in the chronological order of events determined (e.g. Bowes, 1968). Similar zones of refoliation have been described in many parts of the world and some of very large dimension have been recorded as occurring in Africa (Sutton and Watson, 1954, p.51-56; De Swardt, 1963; Hepworth, 1964).

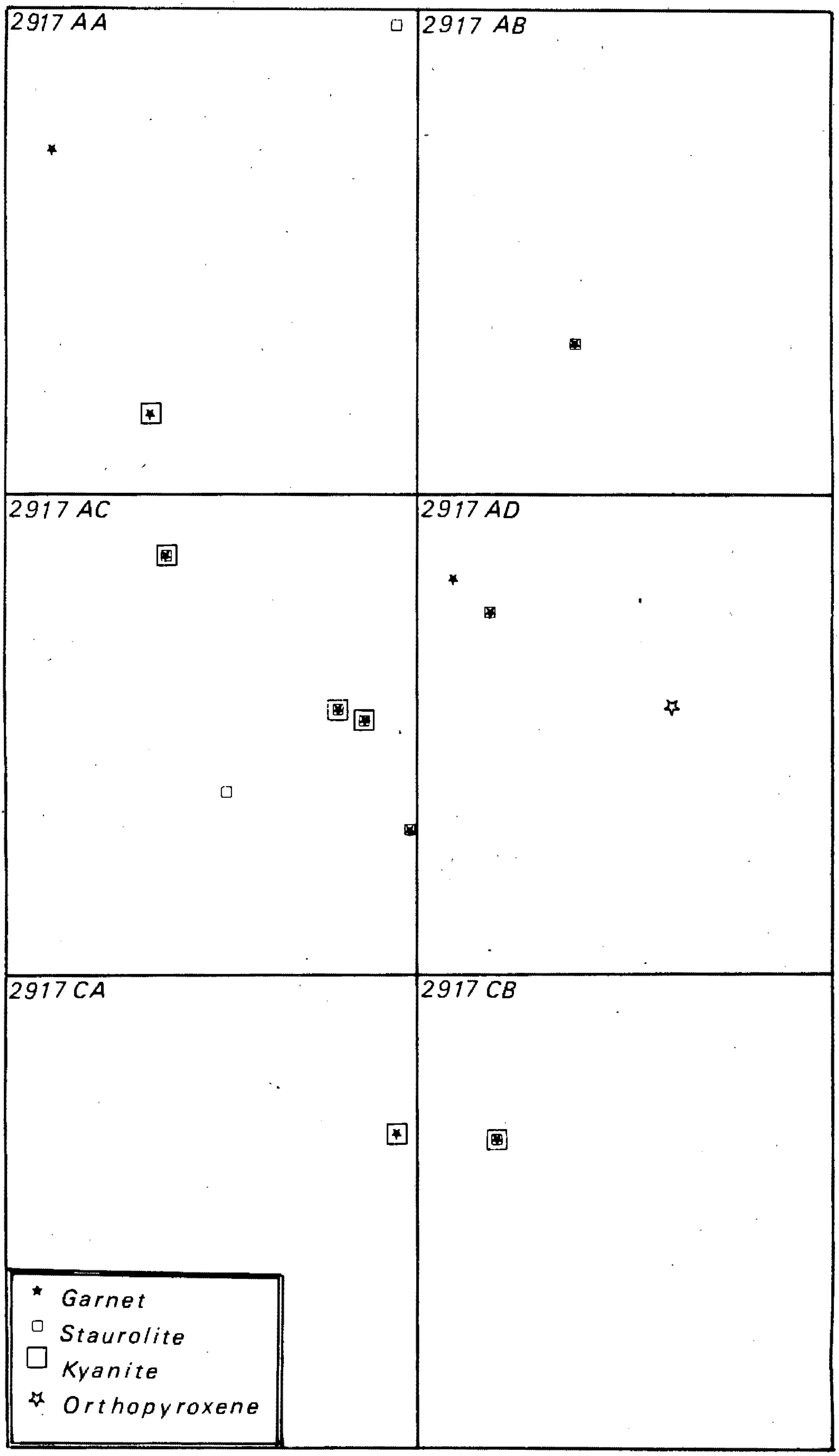
In the present area the shear belts are similar to those described elsewhere in being well-defined zones ranging in width from less than a centimetre to several hundreds of metres along



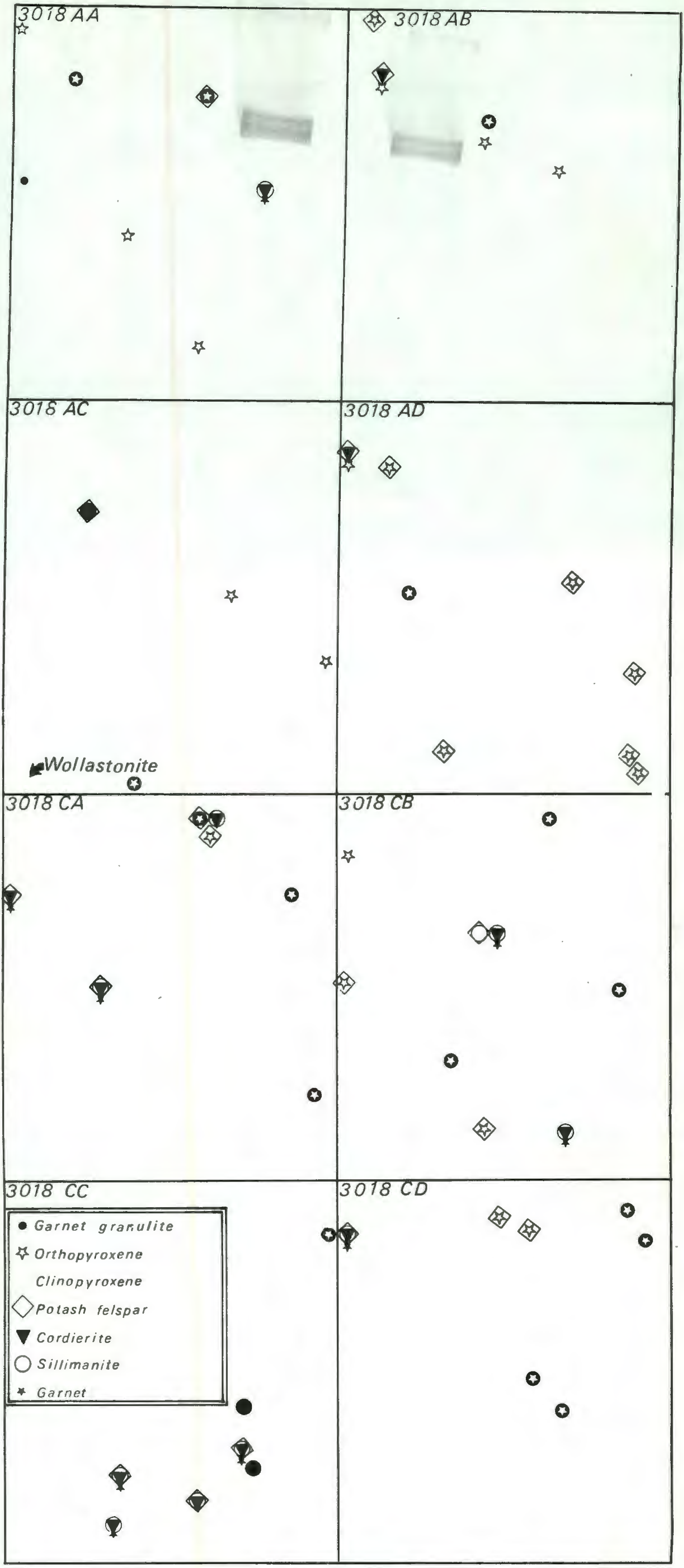
Folder 1 - Distribution of mineral assemblages in the eastern part ˎ7 the area



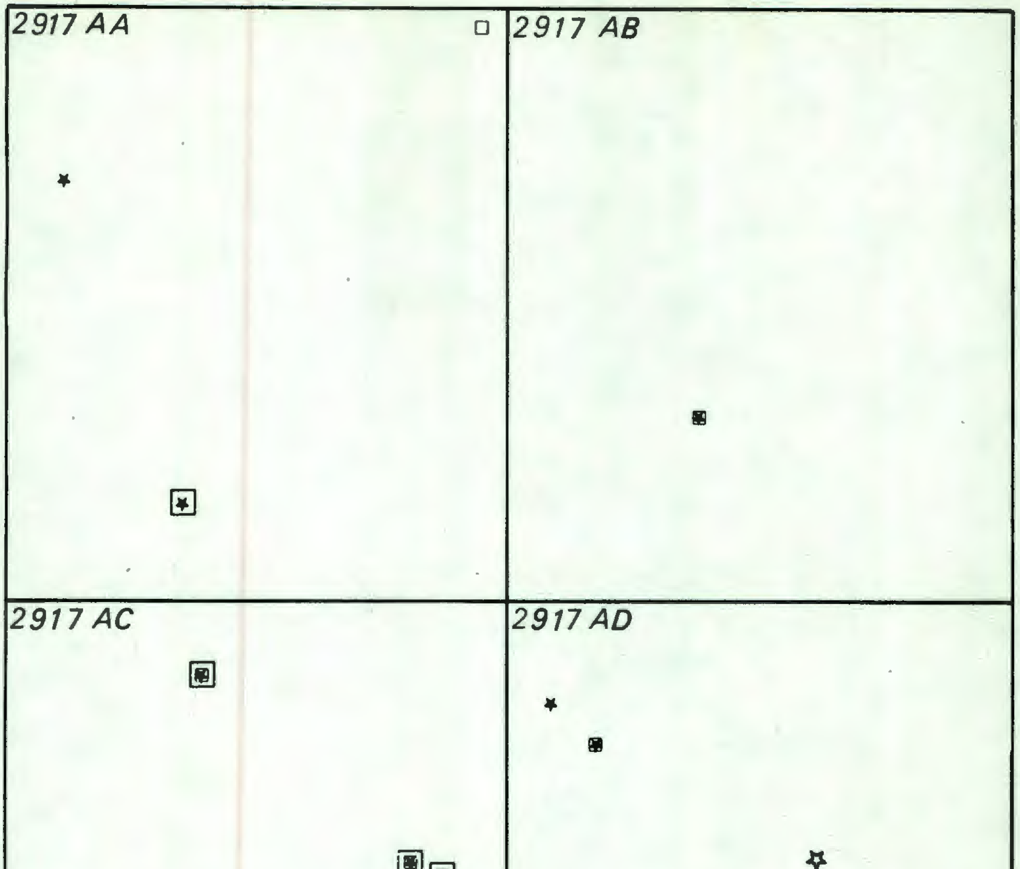
Folder 2 - Distribution of mineral assemblages in the central part of the area



Folder 3 - Distribution of mineral assemblages in the western part of the area



Folder 1 - Distribution of mineral assemblages in the eastern part of the area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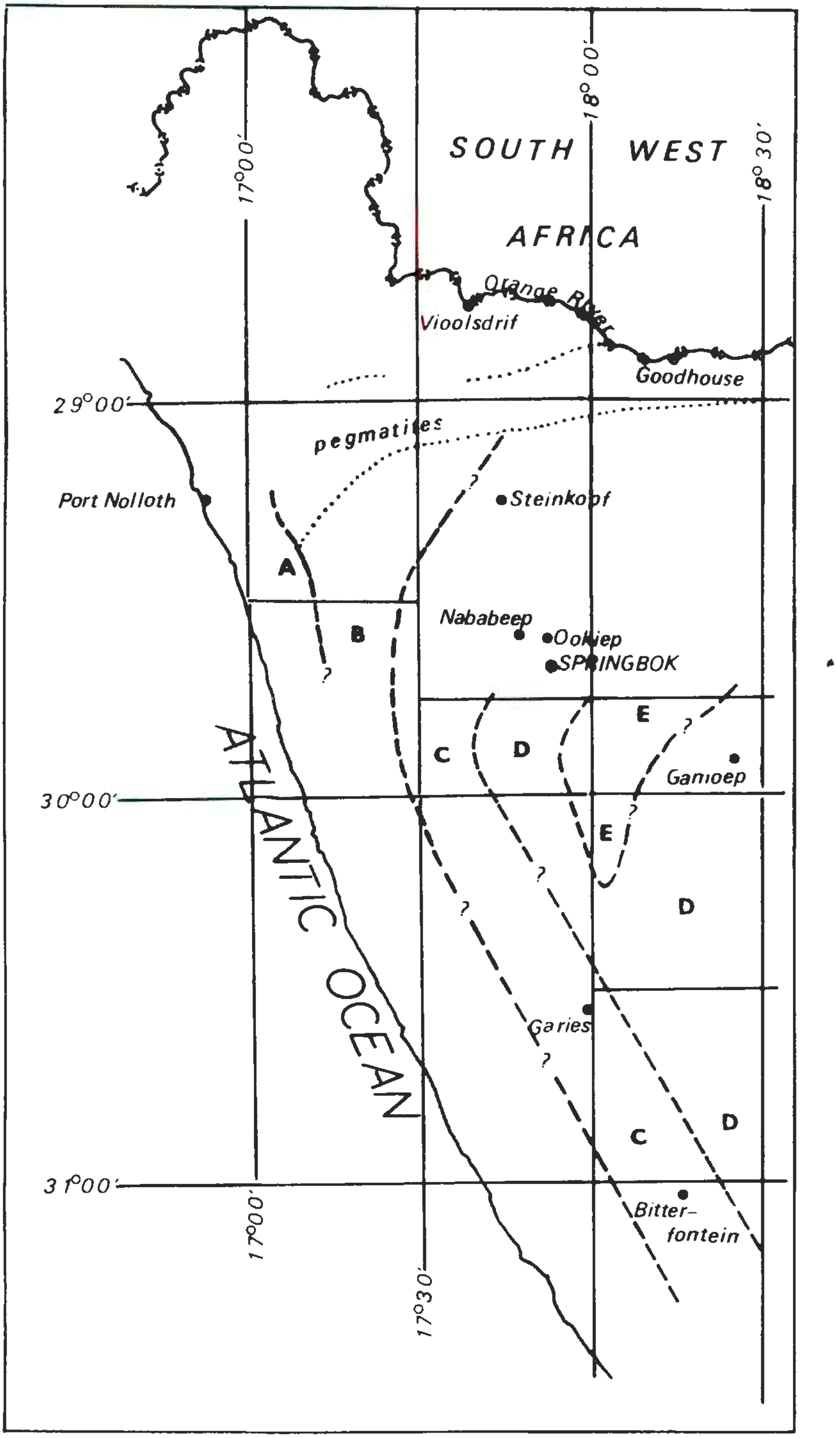
2917 CB



Folder 4 - Metamorphic zoning in Namaqualand which the rocks have been strongly refoliated with concomitant reconstitution of mineral assemblages. They consist of a number of closely-spaced planes along which differential movement took place resulting in zones of finely banded, schistose or cataclastic rocks separated by lenticular masses of varying dimensions where the rocks traversed remain almost unaltered and retain their old tectonic style. They are not always straight but lie in belts of consistent strike and disposition and they often bifurcate, in places re-uniting, or they split up into numerous planes along which slip has taken place. A number of geologists have commented on the abrupt manner in which shear zones die out or become unimportant. As is the case in the present area, Clough (op. cit., p.148, 166) recorded that the refoliation in shear belts is usually vertical, but the dips vary and are sometimes even found to be horizontal.

Many of the shear zones, especially those at higher metamorphic grade during the earlier phases of deformation, tend to follow bands of mafic rocks or have dragged mafic rocks into parallelism along their strike so that they appear on the maps as bands of dark rocks in the acid gneisses.

As the rocks in shear zones are usually schistose and more friable and therefore more easily eroded than the unaltered adjoining gneisses, they most frequently appear as elongated indentations bordered by massive outcrops crossing the hills, and are distinctive on aerial photographs. In other places tight folding associated with shearing has dragged and attenuated quartzites into parallelism along the zone which is then marked by prominent ridges (Plate XIV).

Quartz veins are prominent along some of the shear zones and the paths of these zones in areas of no exposure are marked by the float of white milky quartz fragments. Pegmatites also appear in profusion along some shear zones as small concordant veins and larger pod-like and irregular bodies. In some of the shear zones it is obvious that pegmatites were emplaced at various stages of the development of the refoliation so that the earlier pegmatites have been attenuated and appear as disjointed pods and lenticles while the later pegmatites are undisturbed. The mineralogy and chemisty of similar pegmatites occurring in shear belts have been investigated by Bowes and Bhattacharjee (1967, p.44-46).

The horizontal displacement along small shear zones is quite obvious in the field, but for the large shear belts lateral displacements could not be measured during the present survey. However, it is clear that the larger the shear belt, the more pronounced the lateral displacement becomes and with more detailed investigation, it is possible that displacements along the larger zones will be measured, but measurements would not be as easy as in the Scottish Highlands, where Clough (op. cit., p.151) recorded horizontal displacement of the dykes of up to one and a quarter miles in one instance. Of the number of shear zones investigated

Plate XIV. Hills at Tusschen In formed by thin, highly folded metaquartzites along a major shear zone

by Sutton and Watson (1962, p.96) two-thirds displayed sinistral displacement.

On approaching a large shear zone, there is a gradual change in the strike and dip of the foliation in the gneisses until these are parallel to the shear foliation; changes in the lithology also develop. Hepworth (op. cit., p.40) recorded eight stages of deformation from unaltered gneiss in which banding becomes attenuated and dragged into parallelism through the development of cleavage and a new axial plane foliation which becomes more prominent until finally the earlier foliation is obliterated to yield a crushed or refoliated gneiss. In the present area these changes are well displayed in numerous localities along the margins of shear zones and in a number of places older folds can also be seen to be dragged into parallelism with the shear zone and relict closures of folds and attenuated lenses lie with their longer dimensions parallel to the plane of refoliation. Depending on the lithology of the rocks deformed, the results of shearing are seen as closely-spaced joints in quartzites, flattening of augen, or strongly developed micaceous foliation in the gneisses. The banding of the gneisses becomes disrupted into lenticular pods separated by lines and thin bands of fine-grained micaceous material and the final product of shearing depends upon the nature of the rocks deformed and the degree of metamorphism prevailing at the time of deformation.

Cleavage parallel to the shear zones results in the lamination of the gneisses, and the rocks along the margins of strong shear zones assume a flaggy aspect, while along zones of intense movement lamination of rocks becomes extremely thin due to comminution of the minerals in the rock (Fig. 34).

Marginal flexures with axial planes parallel to the refoliation along the shear zones are well displayed in a number of places and can be recognised without difficulty in banded rocks. The hinge lines of the folds are marked by strong axial-plane foliation which is developed throughout the rocks nearer the shear zone where the folds become tighter and plunge more steeply. Sturt (op. cit., p.142) remarked on the variety of styles of folds encountered and in the present area, large open folds occur away from the shear zone, but as the zone is approached, the folds become tighter to almost isoclinal while in places where the refoliation is less intense, crenulation of the earlier foliation results between the planes of slip. The change from fairly open gently

Fig. 34. Flaggy outcrops of normally massive quartzo-felspathic rocks adjacent to a major shear zone on Steenbok

plunging, to tight steeply plunging folds where folding is accompanied by intense flexural-slip movements, is usually abrupt. The zone of tight, steeply plunging folds is usually comparatively narrow on the edge of the zone of strong refoliation where the folds have been destroyed by further attenuation and disruption. The strongly banded or schistose zone in places contains lenticular bands of almost unsheared rocks. An idealised sketch of these features of a shear zone is given in Fig. 35.

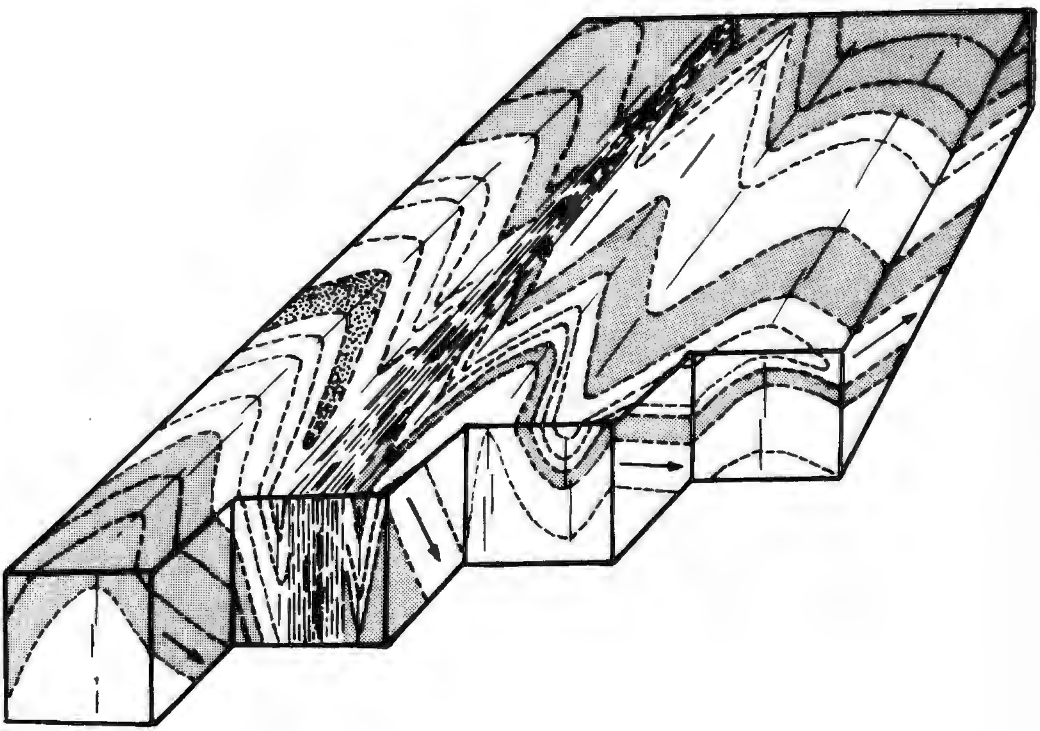


Fig. 35. Block diagram of idealised plan and section of a shear zone showing the mild marginal folds with gentle plunge becoming more tight and steeper in plunge nearer the zone of strong refoliation

Sutton and Watson (1962, p.94) found that, as in most cases in the present area, the gentle plunge of the marginal flexures can be ascribed to the gentle dips of the existing foliation. They also found that the simplest form assumed by these folds is that of a monocline with the banding turning either up or down in the zone of shearing and at the same time becoming greatly attenuated. The shear zones are accompanied by a synformal fold on one side and an antiformal fold on the other. This particular type of folding was rarely encountered in the present area as the shear zone here normally takes the place of a fold itself, so that it is usually bounded by antiforms on either side or, less frequently by synforms along the margins. Some of the minor east-west shear zones are expressed by a gradual steepening of the dip of the foliation up to the vertical, or almost vertical, refoliated zone from where the dip gradually decreases until the normal northerly dip is again attained.

The folding associated with the shear zones distorts the existing lineation and as a result of recrystallisation in the zones, earlier lineations are obliterated and a new lineation takes its place. A new lineation is formed in the hinges of the marginal folds by the intersection of the existing s-plane and the axial-planar cleavage of the new folds and in sympathy with these folds, it usually plunges gently. Where the folds plunge steeply along the edges of the shear zones, the lineations are also steep and in the shear zone itself where the rocks are completely recrystallised, the plunge is down dip, usually almost perpendicular to the strike, but hardly every quite at right angles to it. In the area of tight folding the earlier lineation, now dragged parallel to the direction of shearing, is much distorted and described by Sutton and Watson (1962, p.94) as having been "thrown into loops and festoons on the planar foliations". As noted by Sutton and Watson (op. cit., p.96) the lineation in the shear zone is very different from that of the marginal flexures, and in the present area it is much more strongly developed and usually very obvious.

The steeply plunging lineations and folds associated with shear zones have been recorded by many investigators. For example, Sturt (1961, p.142) in describing the mélange structures, noted that the fold axes have variable angles of plunge which he tentatively ascribes to rotation during the formation of the mélange. He also found, however, horizontal slickensiding on the lenses of the mélange, but a second set of slickensides can occasionally be distinguished at right angles to the first set.

The rocks developed by shearing, as noted above, vary according to the original nature of the rocks deformed and the metamorphic conditions under which shearing took place. The rocks produced in shear belts have been described by many investigators: Sutton and Watson (1951) listed four stages of mineralogical conversion, while De Swardt (1963), admittedly describing refoliation on a much larger scale than the shear zones of the present area, discussed the rock types arising from the deformation and their significance in the interpretation of the geology. The literature on blastomylonites and mylonites is voluminous (e.g. Johnson, 1967). In the present area, shearing in all cases has had retrogressive effects on the existing mineralogical assemblages and it is of interest to note that Clough (op. cit., p.148) stated that rupturing probably took place towards the close of the movements responsible for the shearing.

The evidence for rejuvenation of shearing along existing zones of refoliation is clear in a great number of the belts. It is perhaps most obvious in the shearing of dykes emplaced along the shear zones, but can also be proved by the appearance in places of mineral assemblages indicating a lower grade of metamorphism than that indicated by the assemblage normally occurring along the same zone. Also, the distortion and rupturing of folds, lenses, sheets of pegmatite and lineation obviously the result of deformation during the earlier stages in the development of a shear zone, can only indicate continued and recurrent movement along the same zone.

There is disagreement on the nature of deformation during shearing. Sutton and Watson (1962, p.94 and 96) found in nine of the shear zones examined in detail that "the angle between the flexural axis and the early lineation remains constant and distortion appears to be due to simple bending or flexure folding" while in 14 others this is not the case and they suggest that shear folding may have succeeded flexural folding. The lateral displacement of dykes must be due to a horizontal component in the movement and the lineation was formed perpendicular to the direction of movement. They therefore suggest, because the styles of the structures within the belts are very different from those of the margins and the axes of the marginal flexures are almost at right angles to the crystallisation lineation, that an earlier phase of vertical movement was succeeded by horizontal displacement. Patalakha (1969, p.95) also concluded that preliminary bending of the strata took place prior to dynamic metamorphism when cleavage was superimposed on the folds, and listed (op. cit., p.101) eleven features distinguishing the marginal flexures from the folds within the shear belts. Bhattacharjee (1968, p.258-260) on the other hand, recorded that "while the cleavage folds indicate movement on vertical planes in the shear belts, the drag folds indicate a sinistral sense of movement in them" and suggested that vertical movement along the shear belt was accompanied by a synchronous lateral movement.

Clough (op. cit., p.150) noted that the direction of "lines of stretching" indicate the direction of displacement, so that left-handed displacement is indicated by lineations inclined "with their lower ends on the observer's right hand as he faces north" and *vice versa*. Eisbacher (1970) in his study of the microfabrics of mylonites concluded that if the mineral lineation is interpreted in terms of flow lines, the direction of the major principal compressive stress can be deduced.

Tchalenko (1970) showed that on microscopic, intermediate and regional scales three stages in the evolution of shear zones are characteristic: a peak stage during which the resistance to shear is maximum, a post-peak stage when the resistance to shear decreases, followed by the residual stage during which the resistance to shear is stable though of a lower order than that of the peak stage. He further stated that the mechanism is essentially of the simple shear type during the peak stage, and "at the post-peak stage it is governed by the kinematic restraints inherent in the strain field" while a direct shear mechanism takes over during the residual stage.

Sturt (1961, p.143) found that the shear planes are symmetrically placed as hkl surfaces of the strain ellipsoid and intersect at an obtuse angle to the direction of compression. Ramsay and Graham (1970) showed that the schistosity of shear zones is parallel to the XY plane of the finite strain ellipsoid and concluded that shearing in medium and high-grade metamorphic rocks is the equivalent of slaty cleavage in low-grade rocks.

During the present survey no detailed examination of shear zones was possible, but it appears that the continuous change from gently plunging folds to those of steep plunge, although fairly abrupt, indicates contemporaneous deformation along the margins and in the shear zones, but that the type of deformation changes once the domain of the shear zone is reached. Here too, the shear zones nearly all have left-lateral displacements and their lineations plunge east, north-east or north, but the shear zones across Garies strike west-northwest, have westerly plunging lineations and where lateral displacement could be determined, it was found to be right-lateral.

During his visit to Namaqualand, Prof. J. Sutton expressed the opinion that certain structures showed to him could be compared with Bailey's slides (Bailey, 1910, 1922, 1934), a view with which Dr. D.R. Bowes later concurred. These structures, like shear zones, cause the refoliation, attenuation, strong cleaving and in places mylonisation of the gneisses along closely-spaced planes of slip which are parallel or nearly parallel to the tectonic banding. They display the characteristics as summarised by Fleuty (1964) in that they are associated with folding, accomplish thinning and excision of strata, and show concordance or slight discordance with the gneissic banding. Brecciation is absent, but recrystallised mylonites do occur; the rocks are intensely refoliated in the plane of sliding, the slides are associated with an early phase of deformation, and the gneisses have been subjected to high-grade metamorphism.

In most respects they are similar to the shear zones in having produced the same mineralogic changes as shear zones of the same episode of deformation with strong refoliation, a lineation which is almost perpendicular to the strike along planes of most intense movement (c.f. McCall, 1954, p.165) and all the other features associated with shearing described above; but, whereas shear zones are usually nearly vertical and cut across the banding, the planes of slip of tectonic slides are gently inclined to the north or the surfaces along which movements took place are gently curved.

Tectonic sliding was only found associated with the F_3 episode of deformation and differs from shear zones of the same deformation in that the planes of schistosity are parallel or near-parallel to the banding, and therefore rather more concordant with F_2 axial planes than with those of the deformation responsible for them. It is also possible that they were initiated very early in the history of F_3 deformation, perhaps being the first manifestations, but it is clear that movement was continuous or pulsating over a long period with decreasing grade of metamorphism as indicated by the mineral assemblages occurring along them.

4. The third (F_3) episode of deformation

Folds deforming the earlier structures and resulting in the formation of large periclinal structures due to interference with F_2 folds, occur throughout the area and are responsible for the east-west lithological banding over large parts of the area.

These folds vary greatly in style from place to place, but overall the structures produced are enormous monoclines with subordinate folds occurring as welts along the limbs of the large-scale structures. These asymmetrical folds have long limbs dipping gently north while the comparatively short southern limbs dip more steeply to the south, in places nearly vertical or slightly overturned. In the latter limb minor folding is of the "similar" type (Plate XV) and there is a fairly sharp transition from one type of fold to the other. The minor open folds, on the other hand, occur in the gently dipping limbs of the large structures. The plunge of the folds varies depending on the attitude of the layering brought about by F_2 deformation, so that the F_3 folds generally plunge to the east or east-northeast, but in some localities westerly plunges occur.

In some cases the folds are doubly plunging, not only due to their superimposition on earlier folds, but also as a result of subsequent deformation when brachy-antiforms and synforms having gentle plunges developed.

Small folds are common along the short steep limbs of the monoclines and occur along the hinge zones of the major folds, but

Plate XV. Similar folds in the mafic rocks at Tweefontein

outside these belts minor folds are not as conspicuous. The folds vary greatly in size, from a few cm from crest to crest in strongly refoliated zones to more than 25 km in the large-scale structures, but the latter always consist of a number of smaller congruent folds of similar geometry. In strongly refoliated zones there are flexural-slip folds but the less obvious minor folds appear to be of the flexure type (Plate XVI). The F_3 structures can be compared to the "flexural-flow" folds described by Skinner et al. (1969).

Viewed from the west, the large folds are step-like and Z-shaped with the short steep limbs occurring along the zones of strong shearing and refoliation. Where the dominant foliation (s_1) lies across the direction of s_3 foliation, the relations between the earlier and the s_3 foliation are clear, but where the lithologic layering is subhorizontal as in the northern regions of the eastern part of the area, the foliations are subparallel and the distinction is not as obvious. Vertical or near-vertical s_3 axial-plane schistosity is penetrative in the hinge zones of the folds and in the case of major folds, is found to be continuous, sometimes as a zone of shearing, over many kilometres. Elsewhere lines of slip do not show appreciable

Plate XVI. F_3 folds at Bontekoe also showing interference structures

prolongation along strike and display slight irregularities in strike, but are always almost due east-west or east-northeast, depending on the geographical position. The most obvious mineral in the s_3 axial-plane foliation is biotite, and flaggy rocks with shimmering fracture surfaces are typical of F_3 deformation.

Strong refoliation is also accomplished by tectonic sliding which, for the greater part, is parallel to the banding in the rocks or slightly oblique to the foliation of earlier phases of deformation.

Lineations as intersection between s_3 and the dominant foliation are usually poorly developed and only rarely do mullion and boudinage structures result from F_3 deformation. Crenulations develop when the planes of slip are closely spaced and in zones of strong refoliation mineral lineation is imparted by the dimensional orientation of aggregates of biotite, rods of quartz, hornblende and occasionally even needles of sillimanite. While the trend of the lineation in the axial plane of foliation is parallel to the trend of the folds, the plunge varies considerably and the steepest plunge is always found in zones of strongest refoliation. Rod-like bodies lying at a high angle to the fold axes described by Johnson (1962, p.36) appear to be similar to the structures here and while Johnson described the direction of plunge of the rods as paralleling the direction of shear-slip in the axial-plane foliation, in the present area the lineation behaves the same as in the shear zones described above.

However, in the refoliation planes of the tectonic slides, usually dipping at gentle or moderate angles, the lineation behaves in the same way and variations both in the trend and, to a lesser extent, in the angle of plunge are found. Along planes of tectonic sliding where the movement has been most intense, the lineations tend to be down-dip, in some cases nearly at right angles to the strike of the dislocation whereas, along the margins of the zone of sliding where movement has been less severe, lineations plunging nearer to the horizontal and to the line of strike of the slide are apparent.

The s_3 axial-plane foliation direction is often marked by thin white layers along which translation took place with concomitant folding or curving of the existing foliation (Fig. 27), and these extend into, or their place is taken by, acidic veins. In places it appears that incipient formation of the aplogranites, which most probably only reached their maximum development during the succeeding episode, occurred during the F_3 deformation and that along the hinge zones of the folds a stage was reached allowing the formation of mobile material.

(a) Folds of F_3 deformation

Folds of tremendous proportions trend east-west across the area as shown by large closures in the paragneisses and the curvature of the axial planes of F_2 folds. The existence of at least five such folds, averaging 15 km in wavelength can be proved and it is tempting to divide the area into a number of similar-sized folds but in some regions the presence of large-scale folds is possibly masked by smaller congruent folds, ranging in size from three to more than eight kilometres in wavelength. However, if a distance of approximately 15 km is taken as the average wavelength and measured in accordance with the position of known large-scale folds, it is possible that at least eleven such east-west folds traverse the area mapped. However, the smaller congruent folds of about six kilometres across are clearly expressed in the closures and changes in dip and they are usually of the monoclinal shape as described above. They resemble the folds associated with shear zones on a grand scale if the steeper short limb where strong refoliation took place is taken as representing the shear zone which is then bounded by an antiform to the north and a synform to the south.

In the south of the area a distinct synform is situated in the area underlain by the dark streaky gneiss there. This is a wide, open structure with its southern limb at Soutfonteinkop and the northern limb to the south of Pramkop (3018CC), a distance of more than 15 km. This synform is different from the large-scale folds of the same generation farther north in being more symmetrical and without the vertical, strongly refoliated northern limb. It would appear that the intensity of F_3 folding declines towards the south although folds of smaller dimensions are still present farther south. At Louws Cyfer in the south the existence of a synform closing to the west is distinctly marked by the quartzite ridges there while the closure on Soutfonteinkop is a fold of the earlier generation, which to the north-west of Soutfonteinkop, is folded round the closure of an antiform of the F_3 generation. Like the large-scale structure, the smaller F_3 folds here plunge gently to the west. The continuation of this fold towards the east is perhaps expressed in the present attitude of the F_2 folds in the inliers of basement in Nama sediments there. At Guaapseberg (3018CD) the F_2 folds plunge to the north-east, having swung from an east-west trend, and at that locality a periclinal structure is formed by an F_3 antiform superimposed on an F_2 antiform. At Langedam to the north-west the trend of the F_2 folds is to the north and north-northwest and this trend is also evident at Groothoek from where it swings to become north-west farther west. The s_3 refoliation is strong in zones across the large-scale synform, but not as continuous as similar zones farther north. However, intense refoliation was seen just south of Uitspanberg and in the inliers farther east at Besonderheid and south of Langedam.

Large-scale F_3 folds may exist north of the synform described above, but if they are present, they are not clearly defined and their occurrence can only be inferred from the large folds to the south and north. Their presence is possibly also indicated by the distribution of rock types with rocks of the lower part of the succession mostly exposed in antiforms and the upper part of the sequence most prevalent in the synforms. The recognition of large folds would also be complicated not only by the wide belt of shearing across the region, but also because of the appearance of much granite there as well as the numerous folds of smaller amplitude of the F_3 generation.

To the north of the wide shear belt from Wilgehout Fontein (3018AC) in the west to Draaihoek (3018BC) in the east and in the hills between Draaihoek and Kootjesfontein to the north, several smaller folds of the F_3 generation, trending east-west, have been seen and result in such structures as the periclinal basin at Witplaat. The dimensions of these folds are all approximately the same and the distance between the crests of antiforms to the troughs of the adjoining synforms measures approximately three to four kilometres. To the north the symmetrical closure on Zakkies Berg and Zee Kloof (Fig. 29) is a typical example of an F_3 fold away from the effects of shearing. Folds with almost symmetrical closures are also obvious in the southern halves of sheets 3018AC and AD and whereas the folds to the south cannot be followed for long distances along their axial planar strike, these more northerly folds can be followed for most of the distance across the width of the area mapped, and their effects only appear to taper off on the eastern side of the area. The folds plunge gently to the west on the eastern side of the area while west of the major faults between Remhoogte and Zakkies Berg, the plunge is to the east. The change of plunge is thought to be due to the attitude of the banding brought about by the earlier F_2 folding.

A large antiform of the F_3 generation is situated at and north of Slagieskop trigonometrical beacon and tight folds of the F_2 generation are curved into an almost symmetrical fold there, but in the style of the F_3 folds, this antiform has a gently dipping northern limb and a steep, in parts vertical, southern limb. Around the closure of this fold and also in the smaller antiform to the south, schistose rocks have been produced by shearing. The strong lineation associated with the schistose rocks on the nose of the closure is down dip as is usual with strongly sheared zones, but on the northern, gently dipping limb of the Slagieskop structure where shearing is less intense, the angle between the strike of the shear zone and the plunge of the lineation is smaller. This shearing appears to have been accomplished by movement along F_2 axial-plane surfaces during F_3 folding as envisaged by Ramsay (1967, p.546-548).

From Eselsfontein (3018AC) in the west to Platbakkies (3018AD) in the east, there is a strong zone of refoliation and shearing, consisting of several shear zones along a belt more than 3 km wide. The rocks there have been converted to schists and strongly banded and lineated gneisses and the type of rocks produced depends on their original nature. The porphyroblastic gneisses become almost schistose with flattening of the porphyroblasts in the plane of shearing, the paragneisses change to strongly banded gneisses in which sillimanite appears, and the massive quartzo-felspathic rocks are transformed into red-weathering flaggy schistose rocks in which sillimanite appears prominently and imparts the lineation to the rock. However, the lineation is not as strongly developed as in other shear zones and generally plunges gently or moderately to the east or north-east. The overall dip of the surfaces of refoliation is to the north, but is variable in being almost vertical to steep northwards in the west, becoming less steep towards the east and where the trend of the shear zone swings around the Slagieskop structure, the dip has decreased considerably and the shearing is indistinguishable from the tectonic slides elsewhere.

To the north of the shear zone, where the F_2 folds are recumbent, the fold traces of the third episode have changed direction and they now trend to the north-east. At the same time the structure of this area differs from that of other regions in having curved tectonic slide planes so that gentle southerly dips of the planes are recorded. Tectonic sliding is more pronounced in this part of the region than anywhere else in the area mapped and most probably took place along the axial planes of the earlier recumbent folds, according to the concept of Ramsay (op. cit.).

The movement seen as tectonic sliding on the southerly limb of the antiform south of Leliefontein trigonometrical beacon (3018AC) is responsible for the occurrence of sillimanite there (De Jager, 1963).

In the synform farther east, the gneisses have been folded into a mild shallow basin and the plane of shearing parallel to the existing foliation is therefore also folded into the same shape with the sheared rocks exposed around the circumference of the structure. This feature of folded and curved shear planes is seen in the large synform outlined on the eastern side of that region on the farm Riembreek and farther south-west, but is most strongly folded in the dome on Couragie Fontein. In all these localities movement took place along the existing foliation planes in augen gneisses, resulting in rocks which are almost schistose with the white augen drawn out into ribbons, and the rock consequently has a banded appearance (Plate XVII). The sheared rocks weather more easily than less deformed gneisses and the zones are red or yellow weathering and as they are nearly horizontal, the impression of a bedded sequence in the hills is given (Fig. 36). At Riembreek small hummocks, basin-and-dome structures, each structure only a few metres across, were produced by the interference between F_3 folds and the succeeding deformation.

This domain is also different from those to the south and to the north in the en echelon distribution of the antiforms from that across the Leliefontein beacon to the Couragie Fontein dome,

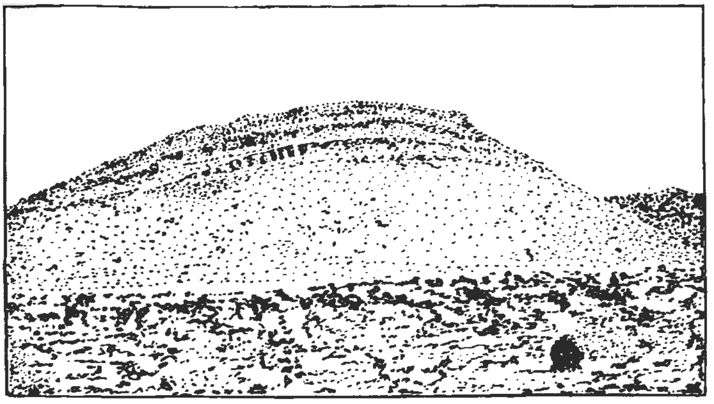


Fig. 36. Bedded appearance of gneisses resulting from movement along subhorizontal planes south of Couragie Fontein

Plate XVII. Sheared augen gneiss produced by tectonic sliding south of Couragie Fontein

with left-lateral displacement indicating anticlockwise movements as explained by Campbell (1958). In this part of the region the structure is complicated by folding of the F_2 episode with fold traces parallel to those of the F_3 folds and also by tectonic sliding. This domain terminates to the north along a dislocation zone which stretches from Modder Fontein (3018AA) in the west, dipping at approximately 20 degrees to the east and striking north-west, but gradually swings round to an east-west strike with concomitant steepening in dip to the north, and farther east at Paapkuils Fontein (3018AB) the strong refoliation is vertical. The change in dip from gentle to steep is thus from west to east and opposite to that of the shear belt farther south.

North of this line of shearing, a well-developed open F_3 synform lies with a trace trending eastwards across the country from De Kuilen plunging gently to the east. In the synform, as defined by the closure to the north-west of Couragie Fontein, the shear plane also forms a shallow synform, but it appears to slice the layering at a slight angle and the plunge of the fold as defined by the shear plane is not parallel to the lineation (l_2). The plane of this tectonic slide again gives the impression of a bedded formation of red-weathering rock in the fine-grained biotitic gneisses there (Plate XVIII). The rocks resulting from the sliding at this locality also contain sillimanite which does not display directional orientation and the central part of the zone is a completely recrystallised mylonite simulating a fairly coarse pink and white quartzite in appearance.

The periclinal synform just to the west of Rooifontein trigonometrical beacon (3018AA) indicates a change in the trend of F_3 folds and at the same time there is an increase in the magnitude of these folds. The rocks become more strongly folded so that exceptionally well-formed periclinal structures resulted from the superimposition of F_3 folds on those of the F_2 generation. The traces of the F_3 folds trend almost east-west on the western side of the map, swing to the north-east for a distance of some 18 km and then resume their almost east-west trend. East of Rooifontein beacon shearing along east-west zones is very prominent. Along these zones small amounts of sillimanite are commonly found and in places mylonites similar to that described above.

Plate XVIII. Gently curved zone of movement marked by recrystallised rocks, seen as a dark band on the photograph, in biotite gneisses south of Rooifontein

To the north of the periclinal structures a well-defined mafic belt representing a deep trough of the F_2 generation, traverses the area. Along this zone the F_3 folds become tighter and are more closely spaced. Strong shearing with the development of new sillimanite in the aluminous rocks as well as alteration in the mafic rocks is featured along the mafic belt. Also noticeable is the change of strike of the mafic belt which almost coincides with the change in trend of the F_3 fold traces farther to the south; for the eastern part of the belt, the trace of an F_3 synform is coincident with the trough of the earlier episode of folding so that the quartzo-felspathic gneisses overlying the mafic rocks in the east represent a repetition of the succession with these gneisses preserved along the down-folded zone.

North of the mafic belt, where mostly Nababeep gneisses are encountered, a major antiform is situated, with its complementary synform at Silverfontein. From the mafic belt in the south to the southern limb of the next major synform in the north, is a distance of over 15 km, but the smaller synform, about 5 km wide and continuous from north of Rietfontein (2918CA) to south of Koornhuis (2917DD) and farther west, assists greatly in the elucidation of the structure. The repetition of similar lithologies due to F_2 folding is quite striking and the expression is an almost symmetrical synform. This synform is bounded in the north by strong shearing of which the refoliation planes dip steeply north, and in the south by tectonic sliding while zones of shearing are prominent all along the structure.

The tectonic sliding is most pronounced in the hills between Silverfontein and Rietfontein and while the effects taper off towards the west, the rocks are strongly schistose over wide zones in the east where the rocks disappear under the superficial deposits of Bushmanland. On the southern side of the hills the planes of refoliation dip to the north generally at about 40 degrees, but the dip decreases towards the north so that dips of about 15 degrees were recorded there and the refoliation appears to cut across a steeper banding of the rocks. The structure here may perhaps not be a slide, but a gently dipping shear zone with a strike concordant with that of the banding.

The gneisses are similar to those described for the tectonic slides farther south, but they have not been completely converted to schistose rocks. The pelitic rocks have a distinctly laminated appearance and like the gneisses, they are yellow weathering. In zones of most intense movement sillimanite has formed and this mineral imparts a lineation to the rock which in this case plunges approximately north and almost perpendicular to the strike of the foliation. In zones where the refoliation is less strongly developed, the lineation is subhorizontal and almost parallel to the line of strike; along this zone small unsheared bodies of anorthosite were found while many small basic intrusives mark the zone of refoliation. Some of these mafic bodies have been sheared so that they now appear as microcrystalline dense rocks while others are coarsely crystalline and black with hornblende showing distinct dimensional orientation. Mafic bodies also occur in the hills of Nababeep gneiss to the west of Silverfontein where they lie along fine-grained zones in the gneiss and these are thought to represent similar zones of movement.

Sillimanite is commonly found along the belt between Silverfontein and Rietfontein and in two localities corundum as small crystals were found on the surface along the belt, but this mineral has not been identified in any of the thin sections.

The F_3 synform responsible for the Silverfontein structure can be followed across the total width of the area mapped and can be followed to the west across the adjoining sheets 2917DD and DC by the presence of remnants of mafic rocks along its strike. South of Koornhuis, structures typical of cross-folding lie along the westerly extension of the fold as defined by the mafic gneisses there.

To the north a minor antiformal fold separates the Silverfontein structure from a zone of strong shearing which, in the east, dips north at about 60 degrees but less steeply towards the west. Along these shear zones the rocks are strongly foliated, finely banded and slivers and large phacoids of mafic rocks have been pinched into the refoliated gneisses. The composition of the rocks traversed by the shear zone controls the new minerals formed and in some places sillimanite is much in evidence and in other localities along the strike, small garnets formed. This zone can be followed across the area to the west, but its effects decrease in intensity in that direction and at Keerom (2917DC) the strong transposition of the eastern part of the zone has declined to fairly closely-spaced lines of slip along which biotite formed and caused the crenulation of the s_2 foliation. In the same area, both to the north and to the south of Koornhuis, fine-grained, almost aplitic, acid veining parallel to s_3 is prevalent and in some localities becomes very numerous in the basal gneisses. All these structures and bands show a gradual change of strike from east to west. In the east the strike is almost east-west and towards the west the strike of foliation, the plunge direction of the axes of the F_3 folds and strike of the acidic banding gradually changeto ENE-WSW. This same feature is seen in the large-scale synform to the north and it appears that the change in strike is probably mostly due to later deformation.

The large synform to the north of Koornhuis is perhaps the best defined of all the major structures as its closure at Komaggas is outlined by the hills of prominent quartzites and schists. The mild curvatures in the southern limb of this synform in the east are the clearest indications of the mild congruous monoclinal F_3 fold there, but the existence of minor folds can also be detected in changes in dips of the foliation in the gneisses. These minor folds within the confines of the large synform increase in amplitude farther north and as a consequence become more prominent. Thus, south of Buffelsrivier trigonometrical beacon (2917DA), the closure of a fairly large antiform, approximately 6 km across and plunging gently to the east, can be seen. Several fairly large shear belts with near vertical foliation are found in the area striking parallel to the trend of the folds, the most prominent being on Dansekraal (2917DD) while major shear zones also occur in the area north-west of Sannagas (2917DC). In the latter area the shear zones are seen to take the place of synforms so that the zones are separated from one another by antiformal folds. Where these zones traverse the coarse porphyroblastic gneisses, the rocks develop stronger, more distinct foliation as the zone is approached, but the contact of the refoliated zone is sharp and includes conformable fine-grained bands of leucogranite.

When the trace of the antiform just south of Buffelsrivier beacon is followed to the east it is seen to be continuous with the "Springbok dome" of Benedict et al. (1964, p.259). Farther north in the present area, exposures are poor, but the existence of folds of the same trend and generation is obvious in the O'okiep area, the most clearly defined being the "Ratelpoort syncline" (Benedict et al., op. cit.) forming the structure across the northern part of their map; this appears to be the easterly extension of the synform across the present area with an axial trace just to the south of Nuttabooi beacon (2917CB). Between this syncline and Kniebrand beacon (2917AB) farther north, the traces of four corresponding folds can be identified by changes in strike and dip in the biotite gneisses of the area, and the most northerly synform which crosses Wit Klip Hoogte resulted in the periclinal structure there by its superimposition on an F_2 fold.

In the northernmost corner of the area another synform of the F_3 generation is clearly defined by the quartzite and mafic rocks there, while farther south towards Kniebrand beacon, the presence of granite and shearing of a later phase of deformation, hamper the recognition of large F_3 structures. Similarly, although minor F_3 structures can be identified in numerous localities farther west, the recognition of large-scale structures of this generation is inhibited by intense shearing and deformation during subsequent events.

As the coast is approached, the trends of the east-west folds gradually swing to the south-west and in places locally to south-southwest due to rotation by subsequent deformation, only to resume the south-west trend farther west. The curvature is not as pronounced in the present area as the distinct swing in lithological banding on the map of the Bitterfontein area to the south (Jansen, 1960).

(b) Regional setting

In the O'okiep area Benedict et al. (1964) described the "Springbok dome" and similar structures and their detailed work has revealed that the "Old" recumbent folding was not congruous and was accepted as an earlier phase of deformation. The large structures have smaller folds parallel to them, but these are only locally developed and do not persist for long distances along strike, some being only of local development. The steep northern limb of the "Ratelpoort syncline" as described by them (op. cit., p.259) is consistent with the style of F_3 folding. They also tentatively suggested that the "Springbok dome" is at least older than the last phase of granitisation.

The best description of the F_3 folds was given by Strauss (1941, p.7-10) who noted that the folding is expressed "in general as a series of assymmetrical elongated domes and basins, or brachysynclines whose major axes all trend parallel to each other and roughly E-W". He found, as common in the present area, that the northern limbs of the "brachysynclines" always have steeper dips than their southern limbs and ascribed this feature to orogenic forces acting from the north.

As noted above, F_3 folds are much less obvious in the south than in the north, but Jansen (1960, p.61) recognised "the superposition of the east-west direction on the regional northwest-southeast direction" while Pike (1959, p.16) recorded folds trending east-northeast and associated with mylonites.

In the Richtersveld, cross-folding of the type resulting in the interference between F_2 and F_3 is not described, but von Backström and de Villiers (in the press) found that "narrow pitching synclines and anticlines with elongated basins or saddle synclines" occur from east of Ramansdrif, situated on the Orange River between longitudes $18^{\circ}15'$ and $18^{\circ}30'$E and upstream from Goodhouse. It therefore appears that there is a northern limit to the belt of F_3 folds somewhere to the north of the present area.

North-east of the present area, near Noumaas, Mr. J.H.W. Ward (personal communication) still finds folds of the F_3 type as well as the associated shearing also described by Gevers (1934) in the area even farther east. Continuing in that direction, Coetzee (1958, p.4) found a "doubly plunging anticline" and in the Keimoes area, von Backström (1961) described several periclinal structures resulting from the superimposition of east-northeast folds on isoclinal folds, generally trending north-west. Well-defined periclinal structures appear on the map of the Keimoes area (von Backström, 1963), but to the south in the Marydale-Prieska area and at least south of latitude $29^{\circ}00'$S, no such structures appear on the existing maps. During a reconnaissance survey of the area west of Prieska, F_3 structures were not encountered and it would thus appear that, although the whole of the present area has been subjected to deformation during the F_3 episode, only a zone some 60 km wide across Keimoes was deformed at that time.

(c) Metamorphism (M_3)

Metamorphism during the third episode of deformation is retrogressive and the effects are mostly seen along the strongly refoliated zones. Many regions between the zones most intensely sheared during F_3 deformation contain rocks hardly affected and the original high-grade metamorphism of M_2 survived. There are also lenses and small phacoids within the most strongly deformed zones with mineral assemblages indicating granulite-facies metamorphism and the residuals have escaped the conversions brought about by shearing.

Lenses of mafic rocks occurring along the hinge zones of F_3 folds are usually massive and unaltered in the cores, but they become more coarsely crystalline and banded towards the edges with the development of greenish-brown hornblende and, at their contacts with the refoliated gneisses, they are laminated and fissile with shimmering fracture surfaces. Under the microscope the effects are first seen as the fibrous alteration of orthopyroxene, a mineral which disappears completely as the contacts are neared. Hornblende replacing clinopyroxene becomes prominent and shows strong dimensional orientation while flakes of aligned biotite become increasingly more numerous. At the contacts of the mafic lenses, biotite is the most common dark mineral, pyroxene has usually disappeared and the transition from granulite to amphibolite is complete.

In the quartzo-felspathic rocks and acidic gneisses thin recrystallised bands form along the planes of slip, in places with quartz veins along them,often fine-grained acidic bands are featured, but pegmatitic veining is most frequently encountered parallel to the planes of refoliation. The Concordia-type granites were mainly emplaced after the third episode of deformation, but inception of these rocks occurred as pegmatitic material spreading along axial planes and over the hinge zones of the folds as small phacoliths. Finer grained bands in the granite parallel to the shearing were seen north-east of Komaggas and a lineation in the granite parallel to the refoliation was encountered in a zone on Dansekraal (2917DC).

The finer-grained, streaky or finely banded, friable, more schistose bands in the gneisses signifying refoliation along shear zones and tectonic slides, are also marked by quartz veining and lenses of green epidote. The number of small basic intrusives along the zone north of Rietfontein (2918CC) appears to have been emplaced throughout the history of the tectonic sliding as some are highly sheared and reconstituted, some recrystallised with minerals showing marked alignment, while others are hardly affected by refoliation.

Banding is accomplished in refoliation zones by the separation of the felsic and mafic minerals. The micaceous minerals lie along thin bands separating ribbons of mostly leucocratic constituents, in some rocks still displaying the inherited foliation. Folding of the inherited foliation is seen on macroscopic and microscopic scale.

Sillimanite is one of the most distinctive minerals formed during shearing movements of F_3 deformation, but the mineral of this generation is not confined to shear zones and tectonic slides. It was obviously again formed in the pelitic rocks and new needles of sillimanite are formed in the axial planes of small F_3 folds (Fig. 37). Sillimanite lying in s_2 forms continuous layers and trains of small crystals. However, tight folds of the third episode and mild folds attributed to even later deformation deranged the regular banding and the layers, and in some cases the needles of sillimanite were distorted (Fig. 38). Sillimanite only forms continuous bands in the shear zones where parallelism is strongly developed, but in pelitic rocks not highly sheared, larger crystals of sillimanite lying in the axial planes of F_3 folds do not form continuous layers and the s_2 layers are disrupted and form thickened hinge zones of tiny F_3 folds.

Fig. 37. Folding of trains of sillimanite crystals and the development of new prisms of sillimanite during F_3 deformation

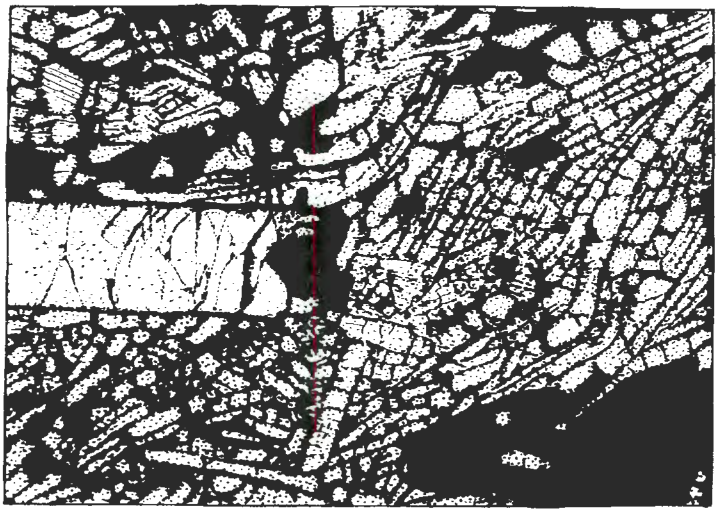


Fig. 38. Bending of sillimanite crystals during F_3 deformation

The sillimanite in the shear zones displays pronounced directional orientation and the rocks are finely banded with ribbons of quartz or felspar alternating with thin layers of sillimanite. In a number of the thin sections examined the sillimanite is altered to sericite which, in some rocks, is iron stained. In several of the pelitic rocks sillimanite is found mantling grains of ore (Fig. 2), a feature also illustrated and described by Brink (1950, p.128-130). Coetzee (1941(a)) found similar textures with corundum forming aggregates enclosing numerous grains of ilmenite and described them as relics of nodular bauxite. In the present area it seems inconceivable that such structures could have survived the intense deformation during the two successive phases of F_2 and F_3.

Felspar is mostly altered in the zones of refoliation with the development of patches of dense sericitic material, and with saussuritisation of plagioclase, epidote appears. Some of the unaltered potash felspar shows uneven extinction and bent cleavage traces, while bent twinning lamellae of plagioclase are seen in all the rocks examined microscopically. Porphyroblasts of potash felspar have been sliced in some instances and sillimanite and biotite appear along the lines of slip.

Quartzites become white and flaggy on shearing with the quartz displaying columnar undulatory extinction and the felspathic content converted to thin bands of fine sericite. The quartz in the other rocks usually appears as highly strained lenticles and has a small 2V in some rocks.

Biotite flakes are well aligned and are found to enclose quartz or small euhedra of sillimanite. In very many of the rocks two generations of biotite can be seen with thin long flakes forming in the axial planes of the folds of the third episode, while the older biotite is more stubby and is often kinked. Biotite is also seen fringing grains of ore.

Garnet is another mineral often formed during F_3 deformation. The banding is seen to curve around porphyroblasts of garnet and in a number of the rocks the garnet contains fine needles of sillimanite which are not infrequently curved, but snowball structures were not found. Small flakes of biotite are found in the garnet and they have the same dimensional orientation as those of the s_3 foliation in the matrix. Garnet rims to grains of ore are also found.

There also appear to be two generations of cordierite. This mineral is usually densely pinitised, but not infrequently is seen as large well-twinned porphyroblasts enclosing sillimanite in layers folded during F_3 deformation and it appears that cordierite was recrystallised during a subsequent phase of metamorphism. Sphene and spinel enclose grains of ore. Ore minerals, unless enclosed by such minerals as sillimanite, when they are coarse, usually show signs of granulation and in one rock examined microscopically, the large amount of ore is concentrated as small folia with leucoxene along the planes of slip. The red colour of the sillimanite schists is due to the oxidation of the ore and the altered sillimanite is often iron stained.

Many of the sheared rocks have mineral assemblages indicating a lower grade of metamorphism than normally encountered along the shear zones. Along planes of slip such minerals as muscovite and chlorite appear and most probably indicate recurrent movement at a later stage. In one of the mafic rocks from Kameelboom (2918CC) chlorite is a prominent constituent.

Apart from chrysotile and phlogopite produced by shearing of the dolomitic limestone as described above, a rock of unusual composition was found on Dabeeb (2918CD) and probably also resulted from the deformation of these rocks during F_3. It is a coarse shimmering mica schist containing black lath-like minerals up to 2 cm long and 0.5 cm across. Under the microscope the large crystals are seen as consisting of a mosaic of even-grained green spinel in a coarse pale brown matrix of poorly orientated flakes of phlogopite. The matrix also contains skeletal crystals of spinel intergrown with small flakes of phlogopite.

As mentioned above, epidote is commonly found along the shear zones and some pale green rocks consisting only of a mesh of clinozoisite crystals were encountered, while other similar types were found to contain epidote, muscovite, a little plagioclase and quartz in addition to clinozoisite.

Cataclasis of quartz and associated kaolinisation of felspar was only seen in rocks where minerals indicating a lower degree of metamorphism occur. However, the recrystallised mylonite from the structure to the north-west of Couragie Fontein (3018AA) mentioned before, is a white rock with pinkish patches and resembles a gritty sandstone. Under the microscope it is seen to consist of a granoblastic mosaic of unstrained quartz and microcline microperthite, a little perthite and a small amount of what appears to be a bleached micaceous mineral. This mylonite forms a band within schistose rock consisting of strained quartz with a little potash felspar and numerous, very small crystals of sillimanite enclosed by quartz. A little iron ore is present and appears somewhat crushed with oxidised rims.

An interesting pseudoconglomerate (Plate XIX) was found at Noupoortsberg (2917CB). The augen gneiss there was subjected to shearing deformation during F_3 and the "pebbles" which display a remarkable degree of rounding resulted from the deformation of the augen themselves.

Plate XIX. Pseudoconglomerate north-west of Komaggas. The "pebbles" have been derived from felspar porphyroblasts

Towards the edge of the sheared zone, the "pebbles" can be seen gradually to lose their roundness and eventually they become the augen of the normal gneiss. In hand specimen the pseudo-conglomerate appears as a dark foliated rock with white "pebbles" and lenticles of quartz and the foliation is seen to curve around the "pebbles". In thin section large dusty altered felspars are seen to occur in a matrix consisting of lenticles of quartz and greenish brown biotite curved around the felspars and lenticles of quartz.

Movement along the shear zones and tectonic slides associated with the third episode of deformation is less intense towards the west and only one such major zone appears in the north-west of the area on Stygerkraal (2917AD) where the sheared rock consists of a fine sericitic mass containing rounded grains of almost unstrained quartz. Altered biotite is also seen in the rock as well as some zoisite and patches of chlorite in the sericite. Towards the west it is even more probable that rejuvenation of movement took place as the coastal area has been involved in intense later shear deformation, but it is certain that the grade of metamorphism during the third episode would have been lower in that direction.

The same mineral assemblages found in the eastern part of the present area along shear zones and tectonic slides of the third episode of deformation are described by Theodore (1970) as occurring in mylonite of high metamorphic grade in the Peninsular Ranges of Southern California. He showed that mylonisation took place at temperatures from 580 to 660 degrees centigrade, close to the minimum melting of granite, and in the pressure range from 3.4 to 7.0 kilobars which equals 11 to 23 km depth. He ascribed the presence of muscovite at such high temperatures as being due to high equilibrium pressure of H_2O.

The shear and crush zones as well as mylonitic rocks have been commented upon by several geologists working in Namaqualand and Bushmanland. Folds typical of this episode of deformation are shown by Pike (1959, map 7) for the area to the south. These synformal folds are situated alongside a shear zone taking the place of an antiform and producing a "steep structure" similar to those of O'okiep (Benedict et al., 1954). Pike (op. cit., p.16) recorded the association of mylonite zones with folding and found that they are distributed <u>en echelon</u>. These mylonites consist of quartz, sericite, epidote and chlorite and the presence of sillimanite is also recorded. Mineralisation followed on shearing and monazite, barytes, apatite, zircon as well as sulphide veins were introduced along the existing shear zones and Pike (op. cit., p.41 and 58) proved that rejuvenation of movement took place at various stages during the introduction of the minerals.

To the north of the present area Strauss (1941, p.47) recorded the existence of vertical bands of fluxion gneiss along which the copper-bearing ore bodies are situated and state "It would appear that the intrusions took advantage of the plane of weakness caused by the discontinuity in the gneiss which the fluxion gneiss constitutes". He further mentioned the pegmatites along these belts and described the anticlinal structures (op. cit., p.71-79) which later became known as "steep structures" (Benedict et al., 1954).

Gevers et al. (1937, p.39-40) gave good descriptions of the shear zones which are fairly steeply inclined or dip more gently to the north in the area investigated by them. They compared the shallow-dipping shear zones to thrusts and mentioned that the zones generally strike east-west or within 20 to 30 degrees of that direction. The converted rocks appear as reddish platy-weathering zones and mylonites in the normal biotite gneiss and they recorded that biotite is changed to chlorite and that epidote is especially abundant. An important conclusion reached by them was that the shearing preceeded the emplacement of the pegmatites which were introduced along north-west fractures of later deformation.

The shear zones have also been investigated near Upington where von Backström (1950, p.39) recorded a two-mile long fracture zone along which the pink aplogranite is converted into a fine-grained sheared, partly schistose rock consisting of lenticles of quartz and somewhat kaolinised felspar with biotite, sericite, chlorite and a number of ore minerals.

5. The fourth episode of deformation (F_4)

(a) General description of deformation

Broad open, nearly symmetrical folds, almost in the nature of warps, distort all the folds described above, but do not materially alter the attitdue of the foliation and layering. The plunges of the folds are determined by the pre-existing attitude of the banding and as the dips of foliation brought about by the preceding phases of deformation in most regions are to the north, these folds generally plunge to the north-west. In some localities, plunges to the south have been recorded. The folds are not regionally continuous, usually of fairly short lateral extent and the distortion of the banding is local.

The F_4 folds are typical flexural folds and the layering is of constant thickness throughout the folds. Some of the folds are monoclinal with the shorter limb to the west (Plate XI) and like the other folds of the same generation, of small amplitude. Although folds of the fourth episode of deformation occur throughout the area, their effects are more pronounced in the eastern part of the area than on the coastal flats.

Small-scale folds are ubiquitous and are defined by small undulations in the banding (Plate XX), locally very abundant.

Plate XX. Mild curvature of the banding in the gneisses east of Garies and typical of F_4 deformation

Occasionally conjugate folds occur with the north-northeast trending axial planes less strongly developed than those of the northwest trend. Small, fairly tight folds are formed marginally to the minor shear zones associated with F_4 folding (Fig. 15).

The axial planes of the folds are usually nearly vertical or steeply inclined to the south-west, but occasionally they are moderately inclined to the south-west. In most areas these planes are almost perpendicular to the pre-existing layering and numerous faults and joints of regional significance indicate continuation or rejuvenation of deformation after the decline in temperature following the folding. In the eastern part of the area minor shear zones are encountered parallel to the axial planes of folds of the fourth episode, all of which have right-lateral displacement and along which the rocks have been retrogressively metamorphosed. A distinctive feature of the axial planar direction and associated fractures is the marked consistency in strike. The minor shear zones on the coastal flats are different in that they are more often found to displace the rocks horizontally in a left-lateral sense and dip steeply to the north-east. Thin leucocratic lines on outcrops mark the position of small fractures along the axial planes of the folds and thin mylonites and flaser gneisses are most frequently found in these fractures of the eastern part of the area. The fractures resulted in structural weaknesses along which pegmatites and the later dykes and quartz veins were emplaced. Granitic pods occur in F_4 folds in places.

Lineations are observed at the intersection of s_4 and s_3 surfaces, and are best recorded in the finely laminated rocks of the F_3 shear zones and tectonic slides where they plunge in the direction of F_4 and at an angle equal to the dip of s_3. Strong lineation was seen only in the large F_4 fold on Dikmatje (3018AB), where it consists of elongated clusters of biotite, and along the shear zones associated with this phase of deformation. Slickensiding and striations on fracture surfaces, probably of a much later age, have been recorded in a number of localities with plunges varying from horizontal to steep northerly.

The structure on Dikmatje (3018AB) responsible for the curvature of the banding and sheared rocks there, is about 2.5 km from limb to limb and plunges gently to the north-west. As the lineation of the F_3 shear zone plunges down dip, it is not always possible to distinguish between the earlier and later lineations.

Cross-folding of a synform of the third episode during F_4 is responsible for the large basin to the north-west of Moedverloor trigonometrical beacon (3018AD), but except for another fold of this generation seen on Bokkraal (3018CB), large-scale folds of this episode of deformation are more mild and are responsible for wide sweeping undulations in the banding. In some regions where the trends of F_2 folds parallel those of the fourth generation, the recognition of the later folds is not easy and some may have been overlooked during the reconnaissance survey. Small folds are commonly encountered and the interference structures formed by their superposition on F_3 folds are seen in a number of places. On the eastern side of Riembreek (3018AB) small basin-and-dome structures resulted, some two to three metres from crest to crest or of even smaller amplitude. Small domes elongated in the F_3 trend direction and less than one metre long occur on the southern bank of the Buffels River on Bontekoe (2917CB) showing that these structures occur in the western part of the area, although of local distribution. Mild folds plunging gently west deform the rocks along the coast south of Kleinzee and these can also be correlated with the fourth episode of deformation as the associated vertical joints parallel to the axial planes of the folds also have the consistent north-westerly strike.

Interference structures between folds of the F_2 episode of deformation and those of F_4 have also been seen in a number of places. Where the F_2 trends are near perpendicular to those of F_4, the relations between the folds are clear and s_2 is mildly curved about the F_4 axes. However, over large parts of the area the two fold systems have common trend directions, such as at the wollastonite occurrence near Garies (Roode Bergs Kloof; 3018AC) and then the first impression is one of great complexity.

Recurrence of movement along the F_4 lines of weakness can be proved to have continued until very much later in the history of the gneisses. Not only are breccias found along some of the fractures but the mafic dykes emplaced along these fractures have been sheared since their introduction and rocks refoliated during the deformation of the Stinkfontein Formation, have been affected by movement along the lines of weakness.

Brink (1950) mentions the presence of grits associated with the metaquartzites in the present area. During the survey only pseudogrits of cataclastic origin related to granulation during F_4 deformation were encountered. These rocks certainly resemble grits consisting of flattened disc-like particules, but under the microscope their origin is clearly seen. The rocks consist of highly strained quartz fragments approaching equidimensional shapes, but with embayed edges, in a fine sericitic matrix. The sericite tends to form bands which include fine grains of quartz and occasional larger flakes of muscovite lying with their longer dimensions parallel to the banding. Crushed and partly crushed grains of ore are also found in the sericite.

(b) Metamorphism (M_4)

Apart from the biotite mentioned above as forming linear aggregates, this mineral is also seen as small flakes in mylonites of the fourth deformational episode where fairly large plagioclase porphyroblasts are also seen in the dense crushed matrix. Sphene appears in some of the tectonic schists of the preceding F_3 episode and as it displays well-developed expansion cracks in the minerals enclosing it, the rounded grains of sphene are probably later than the recrystallisation brought about by shearing.

The occurrence of wollastonite near Garies must be explained as well as the ubiquitous large, fresh porphyroblasts of cordierite which retain trains of fine crystals of sillimanite still distorted in the shapes brought about by F_3 deformation and seen in thin section (Fig. 34). These same rocks also display the mild undulations in the banding typical of F_4 deformation.

Winkler (1967, p.36) recorded that during regional metamorphism where pressures of several Kbars prevail, temperatures of 700 to 800 degrees centigrade are not high enough to allow the formation of wollastonite. One example only of wollastonite as a product of regional metamorphism is quoted and this is the well-known occurrence described by Misch (1964). Turner (1968, p.365-366) questioned the validity of the conclusions and suggested that regional metamorphism of the "Barrovian" type was succeeded, after a substantial break in time and simultaneous reduction in pressure, by contact metamorphism connected with uprise of granitic magma. It would appear that this model suggested by Turner is applicable to the present area and that the wollastonite and porphyroblasts of cordierite formed at the time when the majority of the bodies composed of the Concordia-type granite was emplaced. During his visit to Namaqualand Dr. D.R. Bowes expressed the opinion that the exceptionally large crystals of wollastonite at Garies indicate relaxation of pressure at the time of their formation.

Buddington (1963, p.1161) discussed the difficulties in distinguishing the effects of each of at least two successive periods of intense deformation and metamorphism. The development at high temperature of essentially "dry" granulite-facies mineral assemblages from rocks which may have had hydrous minerals as well as interstitial solutions, followed by the development of orthogneisses from rocks in which the only sources of volatiles were such minerals as hornblende and biotite and at temperatures lower than that of the primary crystallisation, is difficult to understand. He suggested (op. cit., p.1175) that the deformation following on granulite-facies metamorphism facilitates permeation by solutions with H_2O, Cl, and CO_2 to yield new and different mineral assemblages and that a change in T and P conditions is not necessarily signified. Furthermore, the more foliated character of the gneisses would facilitate injection of granite.

More recently, however, Brown and Fyfe (1970), in their discussion on the production of granitic melts during ultrametamorphism, concluded that the granitic melts are not water saturated and that the geologic data indicate P-T conditions during granitic melt formation above the minimum conditions found by Tuttle and Bowen (1958). A series of silicate liquids with compositions appropriate to the granitic family can be produced by the melting of metamorphic rocks containing water only in hydrated phases at temperatures and pressures attained during amphibolite facies metamorphism.

The metamorphism during M_4 can largely be ascribed to the emplacement of granites. The granites of Namaqualand are typical of those of the catazone described by Buddington (1959) as occurring in areas of regional metamorphism at least as high as amphibolite facies. The absence of chill margins, the gneissic foliation parallel to the elongation or peripheries of the bodies and the concordance between country rock and the intrusives are features listed by Buddington (op. cit., p.714-715) and describe the characteristics of the Concordia-type granitic gneiss. Furthermore, the occurrence of porphyroblastic gneisses associated with the granites and the characteristic shapes, such as domes, phacoliths and sheets assumed by granites, together with the above-mentioned features are generally, according to Buddington, interpreted as consistent with late syntectonic emplacement.

The incipient formation of granitic material seen in the sheared limbs of F_3 folds in the form described by Boos and Boos (1934) as the "pine tree" type is commonly encountered on a small scale; this consists of a vertical stem of granitic material branching into and between the adjacent layers. The larger granitic sheets contain xenoliths still with the foliation concordant with that of the country rock and parallel to the margins of the intrusive bodies. Where the intrusive sheets are curved over the hinges of folds, the xenoliths behave similarly and as the foliation of these remnants is still conformable with that of the country rock there, their new orientation does not imply forceful injection of the granite.

Buddington (1959) recorded that many plutons or major parts of plutons have been emplaced by recrystallisation and replacement and that the conversions are accomplished by essentially conformable syntectonic emplacement of magma in the folded rocks. In reviewing the literature Buddington (op. cit., p.722) cited Quirke (1929) who considered the granites investigated by him to be of replacement origin. Gneisses, clearly of sedimentary origin, develop "phenocrysts" and gradually grade into masses exclusively porphyritic where no trace of the original structure or texture has been preserved. Kirkland (1956) considered a granodioritic gneiss to be the more highly metamorphosed equivalent of a meta-arkose. Eckelman and Poldervaart (1957) believed that such features as a boundary zone consisting of intersecting tongues, migmatites and granitic gneisses and the gradation of these rocks along and across strike into the host rocks, as well as concordance between the foliation in the granitic gneiss, migmatite banding and the layering in the metasediments, signify in-place generation of granite.

However, Buddington (1959, p.733) maintained that the syntectonic conditions in the catazone facilitates conformable emplacement of granite and that metasedimentary inclusions in the form of relic folds "are not necessarily 'skialiths' but may be thought of as arising from a complex phacolithic mechanism of magma emplacement into country rock that has complex folds, boudinage structure and formations much thickened and thinned by differential plastic flowage". Some granitisation, hybridisation and partial fluxing of the lowest-melting constituents are only to be expected and the metasedimentary fragments in the granitic gneiss may be either xenoliths or skialiths.

Read (1952) recorded that innumerable examples existed where successively higher grades of metamorphism are cored by rocks of granitic composition and that the classic metamorphic zones are in the nature of thermal aureoles about a focus of granitic activity. In the present area, however, the metamorphic zoning is associated with an earlier episode separated in time from the generation of granite by a period of intense deformation. It would appear that both episodes had a common source of heat focussed somewhere to the east of the eastern part of the present area.

Read (op. cit.) visualised for the gneisses of Namaqualand, amongst others, "varied phenomena of soaking and permeation, of felspathisation and granitisation" and saw such rocks as quartzites, limestones and basic and ultrabasic igneous rocks as "resisters requiring great expenditure of material and energy to convert them into granite". He also considered the alumina-rich bodies not as metamorphosed bauxites, but as "subtractions connected with metamorphic differentiation operating on a grand scale in the juicy setting of migmatisation". In the present area where metasediments with compositions similar to granite exist in abundance, it seems unnecessary to invoke large-scale soaking and permeation and it would also appear improbable that a "juicy setting of migmatisation" could have existed after granulite-facies metamorphism.

In Namaqualand it is true that there are all gradations between leucocratic gneisses, darker and more rarely mafic gneisses in which porphyroblasts grew, to schlieren of the country rock in the granites (Plates III and V) and homogeneous gneiss. Migmatitic facies in the gneisses as well as primary gneissic structure in the granite giving way to areas of homogeneous coarse granite in which no directional elements can be discerned are features commonly associated with the Concordia-type granite. It is tempting to ascribe a replacement origin, with local mobilisation only, to all these granites and certainly a large proportion of the granitic gneisses evidently formed by coarse recrystallisation. The occurrence of metasediments, essentially of the same composition as the granites even in areas intensely intruded by granite and showing only local patches of coarser recrystallisation as well as transgressive contacts in places, indicate magmatic intrusion. It can only be concluded that meta-arkoses remained unaltered when granites appear all round, that the lack of volatiles prevented complete recrystallisation or that the granites were generated at a lower level and were intruded into the position where they are now exposed.

Mehnert (1968, p.241) in discussing the results of the experiments of Tuttle and England (1955), noted that if a "normal" geothermal gradient of 30°/km is assumed, the minimum melting temperature of granite at 640-660 degrees centigrade is reached at about 20 km corresponding to a lithostatic pressure of some 5 Kbar. In orogenic belts, however, the geothermal gradient is much greater and the beginning of anatexis is considered possible at temperatures of 640-750 degrees centigrade and pressures of two to four Kbar.

Metamorphic cycles similar to those of Namaqualand have recently been described by Ebert (1970) in an area in north-eastern Brazil where "a strong static metamorphism is superposed to the dynamic" and rocks with granitic affinities resulted. The structurally controlled emplacement of pegmatites took place during a late phase of deformation when weak folding occurred along the trends of pre-existing folds. Ebert (op. cit., p.1318) further suggested that "granitisation" is restricted to steeply inclined strata which facilitated the rise of thermal energy and the introduction of potash.

In Namaqualand there is ample evidence to suggest that the granites and pegmatites were largely emplaced after the third episode of deformation. The granites and their porphyroblastic contemporaries are not sheared by deformation during that period and the intrusion of granite into the tectonic schists with concomitant development of large pegmatitic nodules in the schists, clearly indicate that magmatic intrusion followed on that phase of deformation. The emplacement of the granite, however, was largely controlled by the pre-existing attitude of the layering brought about by the F_3 deformation. There can be little doubt that the majority of the Concordia granitic gneisses and the associated pegmatites were generated and intruded during the fourth episode of deformation. The accommodation of granite in minor F_4 folds and the emplacement of pegmatites along fractures associated with this episode of deformation are clear indications of the contemporaneity of these structures with the formation and emplacement of the acidic rocks. The emplacement of pegmatites along north-west fractures related to the fourth episode of deformation and their occurrence along a fairly well-defined east-west belt separating rocks of granitic aspect from less-metamorphosed rocks to the north, have been described in detail above (p.70-72).

The structural control of pegmatites occurring in foliated crystalline rocks is summarised by Landes (1942) and Jahns (1955), while Gresens (1967) whose views are supported by the evidence in Namaqualand, presented testimony that pegmatites were formed synkinematically during metamorphism. He suggested that emplacement must have taken place during deformation and that the pegmatite bodies plunge, as shown by their internal structure, parallel to the lineation in the country rock (presumably the lineation associated with that phase of deformation). He also recorded that the emplacement of zoned pegmatites depended upon tectonically-produced low pressure zones.

It would appear, therefore, that the granulite-facies metamorphism of M_2 was succeeded by a period of intense deformation (F_3) which in turn was followed by mild folding and fracturing when granites and pegmatites were generated and intruded into the gneisses of Namaqualand. During the M_4 metamorphism pressure was at a low ebb, but high prevailing temperatures resulted in the formation of much cordierite and some wollastonite. This cycle of metamorphism and intrusion culminated in the emplacement of pegmatites along north-west lines of structural weakness along an east-west belt (Folder 4) separating the gneisses from the less-metamorphosed rocks in the north. This belt appears to represent the edge of the area affected by the M_4 metamorphism to the north of the present area, beyond which the rocks were not metamorphosed during this cycle. The granites were emplaced mainly along the pre-existing foliation, generally in an east-west direction and parallel to the pegmatitic belt. This metamorphic cycle was therefore superimposed along lines almost perpendicular to the existing metamorphic zoning and recrystallisation produced during M_2.

(c) The age of the fourth episode of deformation

The age of ±1,000 My commonly determined in the Namaqualand gneisses and rocks intruded into them has been a point of controversy and a field of enquiry since the data of Nicolaysen (1962) and Nicolaysen and Burger (1965) appeared in print. These rocks have always been tentatively correlated with the Kheis System and the associated granitic gneisses, whose involved structures, compared with the relatively undeformed rocks of Transvaal age, indicate an age at least greater than 1,000 My. Nicolaysen and Burger (op. cit., p.514) considered the possibility of a linear incursion of heated mantle below the Namaqualand-Natal metamorphic zone and the southward accretion of the continent along Southern Africa during the 1,000 My period. Earlier Nicolaysen (1962) ascribed the discrepancy in the age either to an error in the accepted geologic column so that part of the Kheis System is much younger than hitherto supposed, or to a wide-spread regional metamorphism and pegmatitisation affecting the Kheis rocks after the deposition. He (op. cit., p.587) recalled that Schwarz (1910) was of the opinion that metamorphosed Transvaal System rocks constituted part of the Kheis System and called for detailed mapping north-west of Prieska in order to determine possible metamorphic equivalents of Transvaal System and older rocks to the west. It now appears that his second suggestion of a wide-spread metamorphic cycle during the 1,000 My episode is correct.

During the present survey specimens of Concordia granitic gneiss from different parts of the area were submitted for age determination as recorded by De Villiers (1968, p.35). The preliminary ages determined on zircons separated from the granitic gneisses, and their localities, are as follows:- Bokputs (3018AB) 900 My; Remhoogte (3018AD) 962 My; Leliefontein (3018AA) 1,000 My. The age obtained from the porphyroblastic gneiss of Eselsfontein (3018AC) was 983 My. Another age determination from the present area recorded by Nicolaysen and Burger (1965) as being from Garies was collected in the western part of sheet 3018CA and the U-Th-Pb measurement on monazite yielded an age of 920±30 My. To the south of the present area a higher age (1170 My) was returned for the monazite from Steenkampskraal.

As noted before in the discussion on pegmatites, the ages of ±2640 My and 2630 My for granites intruded into the Marydale metavolcanics to the north-east of the pegmatite belt are recorded by Nicolaysen and Burger. However, all the measured ages of the pegmatites along the belt, too many to enumerate, as well as those of other rocks and minerals farther south-west, fall within the 900-1090 My limits. Du Toit (1965, p.65) recorded the significant age of 1,280±50 My for a granophyre dyke traversing the Kaaien quartzite between Upington and Marydale. This dyke is undisturbed while the metaquartzites have been involved in at least two intense phases of deformation (personal observation) and du Toit (op. cit., p.66) also noted that the cycle transects a pegmatite which would presumably date at 1,000 My. It, therefore, appears impossible that an age of 1,000 My could be assigned to the rocks of Kaaien age.

Contradictory age determinations have also been measured in the rocks and minerals of the Moinian and Dalradian of Scotland and are discussed by Dalziel (1969, p.17-18). He recorded that two hypotheses have been advanced to explain the younger age obtained from Moine mica and whole-rocks relative to the age obtained from the rocks of the overlying Dalradian. The first is the "overprint hypothesis" when overprinting in the deeper seated Moine rocks is thought to have been more complete, thus resulting in the younger peak in the ages for the Moine. Alternatively, it has been suggested that the slightly older Dalradian peak is the consequence of more rapid cooling in the higher levels. For the present area it does not appear relevant how the discrepancy in ages came about, but, whatever the process, that the ages are related to a metamorphic event.

It therefore appears that the ubiquitous age of ±1,000 My for the Namaqualand gneisses and their intrusives can be related to the M_4 metamorphism when the metasediments were subjected to high temperature at a time when pressure abated and when the granites and pegmatites were emplaced.

Martin (1969, p.21) discounted the possibility of the 1,000 My age resulting from a thermal event unconnected with an orogeny as the concordance in ages of the zircons and the micas requires complete recrystallisation of the rocks and not just prolonged heating. He offered the alternative suggestion that the 1,000 My province represents "the infrastructure of an orogen stripped by erosion of its geosynclinal pile and its platform equivalents". This postulation does not invalidate the above conclusions.

This situation is not unique to Namaqualand. Similar instances have been recorded from many Precambrian terrains as demonstrated by the expositions, for example, in Wynne-Edwards (1969).

D. THE SECOND EVENT

Following on the largely plastic deformation of the first event, brittle deformation of the gneisses in the nature of shear zones followed. The shear zones are arranged in sets occurring with definite strike directions and those nearer the coast are younger than the shear belts transecting the eastern part of the area. It also follows that a decreasing grade of metamorphism is apparent from older to younger shear belts in addition to the lower degree of metamorphism to which the gneisses were subjected in areas west of the escarpment. Rejuventation of shearing along pre-existing lines of weakness complicates the unravelling of the sequence of phases of shearing, but there can be little doubt that those mostly affecting the area in the east and formed under a regime of amphibolite facies metamorphism, occurred prior to the deposition of the Stinkfontein Formation. Shearing took place in three directions during this event, following on the emplacement of granite towards the close of the first event. The deformation is typical of basement deformation as described for Precambrian terrains elsewhere, but if sediments were deposited on the Namaqualand gneisses before this event, no trace of them has been found or they were not recognised during the present survey.

1. The first episode (F_5)

Although minor shear zones belonging to this phase of deformation have been found all over the area east of the escarpment, the main zone of dislocation lies along a belt from Wilgehout Fontein, west of Garies, across Klein-Kamiesberg (3018CA) to Draaihoek (3018CB) in the east-southeast. In the west the zone is almost eight kilometres wide, but tapers to the east where its effects and width are much reduced. Strong shearing and refoliation are evident along most of the zone and the banding parallel to the strong deformation is even evident on the scale of the map.

The structures associated with this episode of deformation are typical of those of shear belts described above. The shear zones traverse the granites in many places and are therefore later than the folding of the first event.

Considered as a whole, the belt appears to form a large asymmetric structure with generally southerly dips along its northern margins and northerly dips to the south, and as the zone is approached from the south, the northerly dips become increasingly steep. The strong lineation associated with the shearing is different from that of all the other shear zones in plunging to the west, whereas the lineations associated with subsequent shearing plunge either to the north-east or to the north. The planes of refoliation are usually steeply inclined to the north, but dips as low as 55 degrees to the north have been measured. The belt consists of a number of strong shear zones which bifurcate and anastomose, separating relatively undeformed lenticular areas in which open folds and mildly curved foliation surfaces, also plunging gently west, can be recognised.

In the shear zones transposition structures as described by Whitten (1966, p.181-186) are commonly developed (Fig. 39) and the older folds are dragged into parallelism and distorted (Fig. 40), while the inherited foliation is distorted and crenulated. In places of strong shearing disorientated blocks of rock different from the country rock transected, have been encountered (Fig. 41). The older lineations are twisted and curved and on Wilgehout Fontein a specimen was collected in which the sillimanite needles have been bent and sericitised by the shearing.

The granites are refoliated at an angle to the direction of the dimensional orientation of phenocrysts and schlieren, and this results in distinct but irregular banding. Banding is also seen in the numerous small pegmatite stringers (Figs.42) and in streaks of numerous small garnets (Fig. 43). Lineation is seen in lenticular aggregates of dark minerals or in thin lenticles of quartz. The quartzo-felspathic rocks appear more like metaquartzites as a result of shearing, but the most obvious changes are seen in the fine-grained biotite gneisses and mafic rocks. Large garnets, up to 1.5 cm across, develop in these rocks at the expense of biotite and they are all mantled by distinct leucocratic zones. The mafic rocks in places develop gneissosity and appear almost migmatitic. Large felspar porphyroblasts form, aggregating with pegmatitic material which merges with the fine-grained dark matrix and appears as irregular concordant segregations of pegmatitic veinlets, in places ptygmatically folded. Streaks of mafic material are found, resembling small lenticular and concordant intrusives. Quartz veins are prominent along these shear zones and epidote lenticles are also encountered.

The shearing is again prominent in the Komaggas area where the rocks develop a platy character and flaggy outcrops result. The augen gneisses are sheared to yield micaceous bands while the augen have been drawn out to form small phacoliths with their longest dimensions parallel to the lineation.

Mylonites and blastomylonites are encountered in some areas along the shear zones and in at least one area, appear to signify repetition of movement during a later phase of deformation. In several of the specimens collected along the shear belt, two generations of biotite are seen. In one thin section the older biotite is distinctly kinked. An interesting specimen of sheared granitic gneiss, medium to coarse grained, vaguely banded and containing irregular shaped garnets with leucocratic rims, was collected south of Draaihoek. Under the microscope it is seen to consist of quartz, altered felspar and thin bands of altered

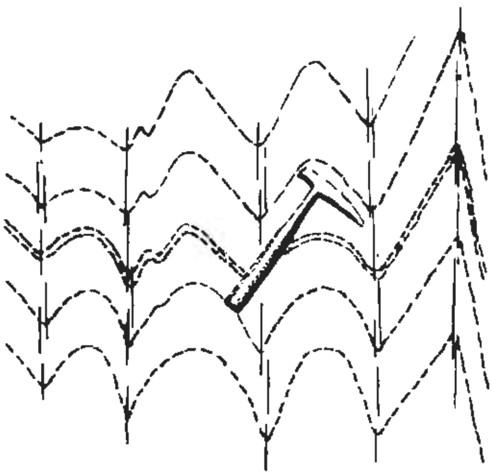


Fig. 39. Crenulation of the foliation resulting from transposition along a west-northwest shear zone, Wilgehout Fontein

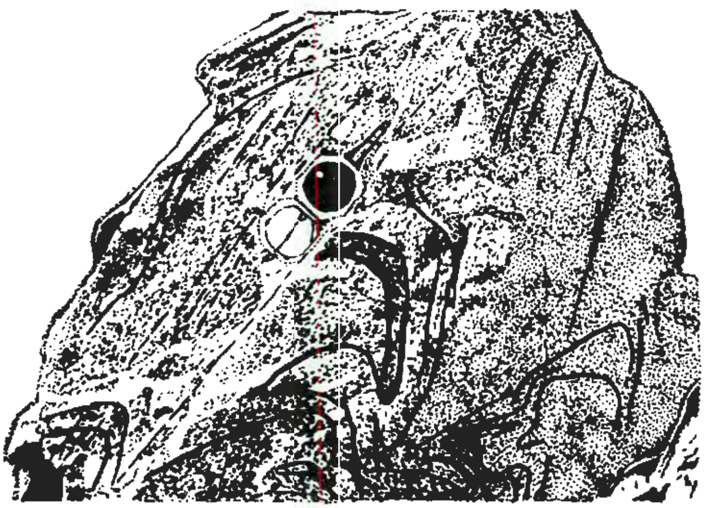


Fig. 40. Distorted folds in west-northwest shear zone, Witplaat

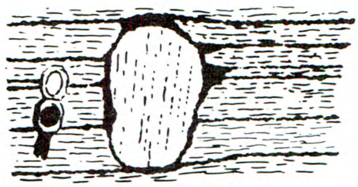


Fig. 41. Disorientated block of unsheared gneiss with rim of white quartz along shear zone showing quartz-rich bands, Buffelsfontein

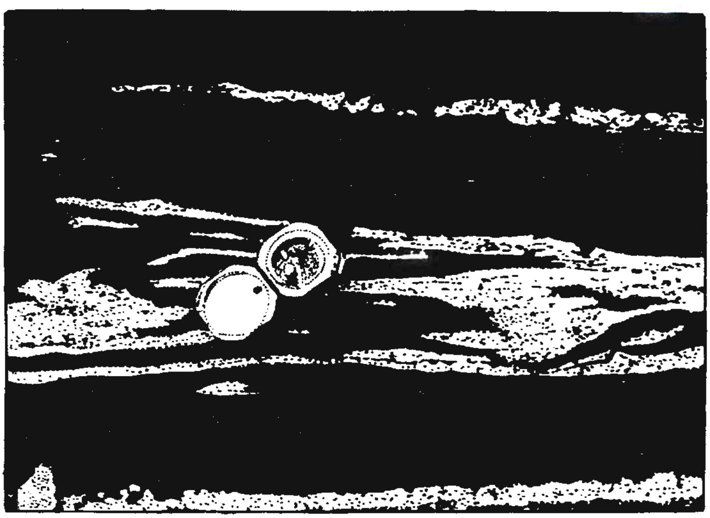


Fig. 42(a) Small stringers of segregation pegmatites in west-northwest shear zone, Wilgehout Fontein

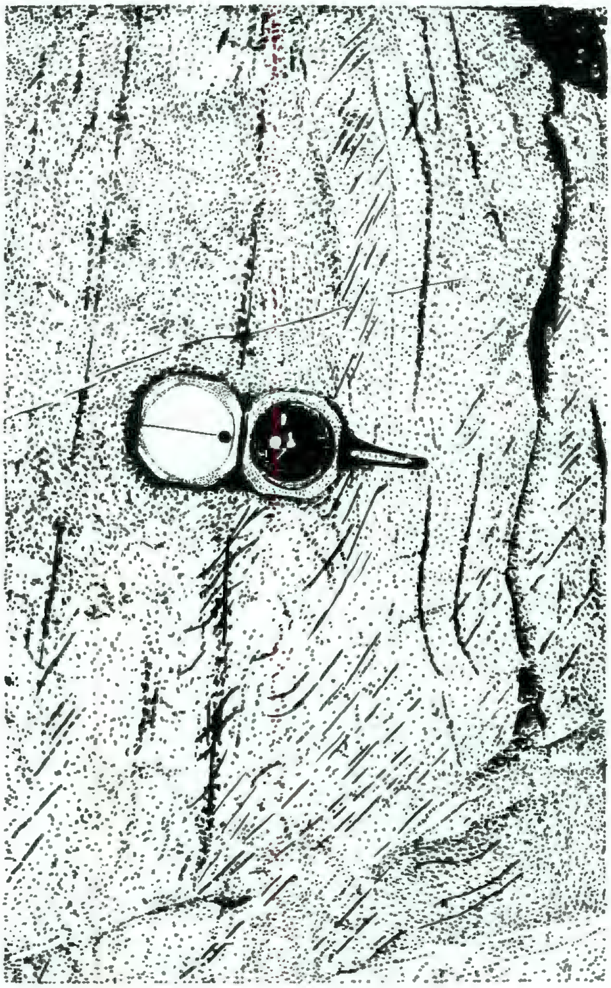


Fig. 42(b) Mild deformation of foliation (S_2?) by movement along planes striking west-northwest (perpendicular to compass) and the development of incipient banding along shear zone, Wilgehout Fontein. An earlier banding (S_1?) is also shown.

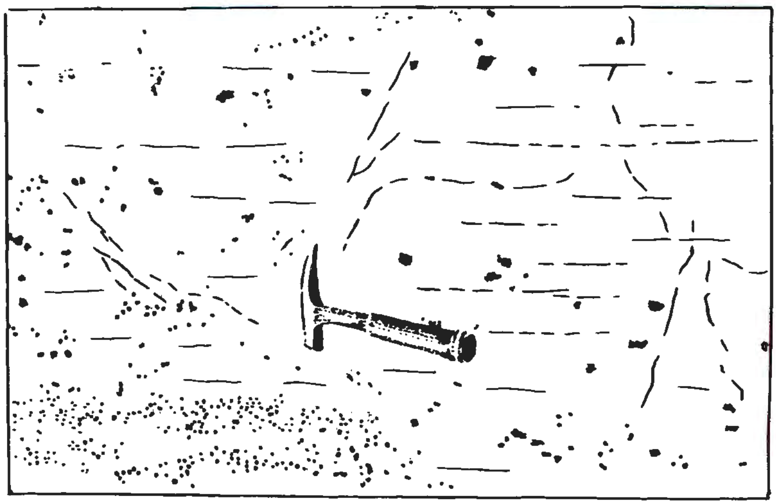


Fig. 43. Streaks and some larger aggregates of garnet in shear zone, Wilgehout Fontein

biotite. The rock is traversed by thin parallel zones of equal width containing calcite and epidote or aggregates of clear recrystallised plagioclase.

The mylonite of the shear zone on the northern side of Brakkefontein (3018CC) is a fine, hard, grey rock with fine felspathic lenticles. In thin section it is seen to consist of fragments of perthite, plagioclase and some quartz in a finely divided sericitic groundmass. There appears to be no obvious banding except for thin ferruginous lines which probably mark the planes along which slip took place.

A shear zone shown on the map to the south of Kommagas is marked by a light brown, highly schistose rock with finely shimmering foliation surfaces consisting of finely crushed quartz with thin bands of sericite containing fine flakes of biotite.

2. The second episode (F_6)

Small folds resulting from movement along planes of slip striking to the north-east (Fig. 44) and in some cases marked by thin leucocratic lines, are common throughout the area and have been found contorting the foliation brought about during the F_5 phase of deformation. In the north of the eastern part of the area shear zones of the same strike direction become prominent and are often seen to take the place of antiforms as they are bounded on both margins by synforms. The effects of these shear zones are comparatively mild in comparison with those of other directions and in all cases the associated lineations plunge at various angles to the north-east or north-northeast with the one exception seen at Witkoppie (2917AD) where a westerly plunge was measured.

Numerous large joint systems occur parallel to this direction of shearing (Plate XXI) and as in the case of the planes of slip, are nearly always vertical, but in the southern part of the area some with moderate dips to the north were encountered. At Banke (3018AD) a pegmatite was emplaced along a minor shear zone, showing left-lateral horizontal displacement, of this phase of deformation.

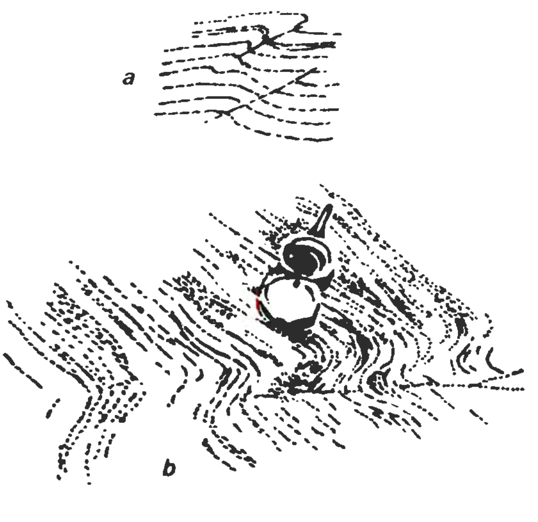


Fig. 44. Small north-east folds;
(a) Dikmatje
(b) Biesies

Plate XXI. Sheared base of metasediments on gneiss showing pronounced north-east joints, Eendoorn

In the central part of the area, between Koornhuis (2917DD) and Komaggas and even farther west, the shearing of F_6 and F_3 are parallel and as the degree of metamorphism of the older deformation decreases towards the west, it is often difficult and even impossible to distinguish between these two episodes of deformation in the field (Plate XXII). As rejuvenation of movement along the same direction appears to have taken place during the later phases of deformation, the situation is even more complicated. North of Komaggas, however, the effects of shearing parallel to F_6 are distinctive and cannot be confused with those of the earlier deformation. Similarly, it is impossible to distinguish between the marginal folds of F_6 and the smaller earlier folds in some places, unless the distinction can be made in the associated shearing such as the deformation of vein-like pegmatitic stringers emplaced along F_3 axial-plane cleavages seen at Langhoogte (2917CB When the planes of slip are closely spaced, transposition structures and crenulations are commonly seen with this phase of deformation. Rejuvenation of the movement is recorded by the strong shearing in a north-easterly direction of a dyke striking north-northeast south of Wildepaarde Hoek and north of Groenkloof

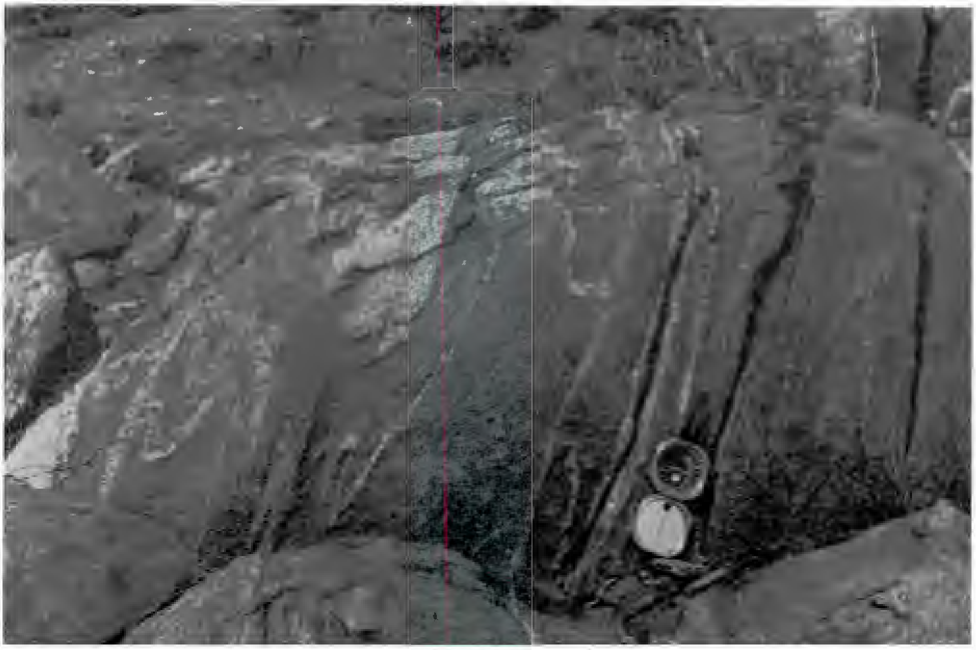


Plate XXII. Two successive phases of deformation in the same direction, Mara River

trigonometrical beacon (2917DC).

From Styger Kraal (2917AD) across Ariroep to Knie Brand in the north (2917AB) several thin bands of quartzitic rocks varying in width from less than a centimetre to more than one metre, lie across the gneisses in straight lines which can be followed for many kilometres along strike. The silicified zones strike perhaps slightly more to the north of east than the usual direction measured along F_6 shear zones, but they have also been deformed by subsequent deformations.

In the east the obvious new mineral is biotite and, as in the case of the previous phase of deformation, pegmatites and quartz veins as well as small lenticular bodies of epidote also mark the presence of the shear zones. To the west the minerals mostly encountered in the shear zones are muscovite and quartz while the biotite present is always somewhat altered and of patchy distribution, perhaps indicating repetition of movement at a later stage. The quartz is always strained and in one of the thin sections examined a thin quartz vein consisting of equigranular quartz grains traverses the rock parallel to the foliation. When felspar is present it also displays uneven extinction. In the north-eastern corner of the area, north-east of Chabiesies (2917AB), a sheared mafic rock showing slightly shimmering foliation surfaces and weathering to a red colour is seen to consist of epidote, chlorite and hornblende in a matrix consisting of quartz and calcite with some leucoxene.

The silicified shear zones appear as hard white flaggy quartzites which are distinctly laminated and strongly lineated. In thin section the rock is seen to be finely banded with alternating bands of quartz of varying grain size. The quartz grains in the fine-grained layers are not strained and appear to have recrystallised when movement took place. Fine bands of very small flakes of muscovite, dimensionally orientated parallel to the banding, are also seen. A very interesting narrow silicified shear zone occurs on the northern part of Ariroep showing all the features normally associated with the shear zones on a small scale. The mild folding in the marginal parts of the shear becomes tighter and more steeply plunging towards the centre of the zone over a distance of less than one metre. Mild folding by a later phase of deformation can also be recognised in the rocks (Fig. 45).

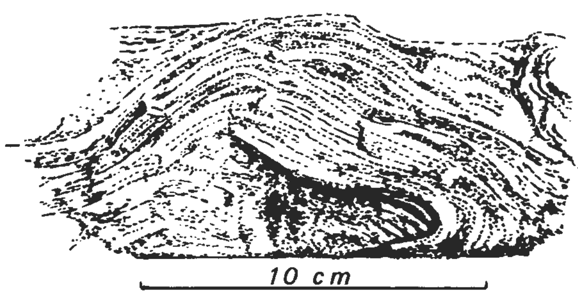


Fig. 45. Tight fold in laminated quartzitic rock of a north-east shear zone refolded mildly in north-northeast direction, Ariroep

It would appear that in these zones silicification is the first manifestation and that these silicified bands become contorted with continued movement along the same lines of weakness.

Another example of a silicified shear zone at Styger Kraal is seen as a 0.5cm wide greyish white quartzitic plate with very strong steeply plunging lineations almost like striations. The rock consists of inequigranular grains of microcline and strained quartz, almost all rounded to some degree and with thin mantles of fine sericite. As the plane of slip is neared, the felspars disappear completely with concomitant increase in the amount of sericite while the quartz grains become noticeably larger and more strained. Along the main plane of slip only lenticles of strained quartz in wider bands of finely divided sericite are found.

In some of these rocks flakes of biotite occur with their longer dimensions parallel to the foliation which is marked mostly by muscovite, but some biotite of an obviously later generation occurs in small clusters in haphazard distribution across the banding.

Without having definite proof, it may perhaps be suggested that the "steep structures" described in great detail by Benedict et al. (1964) as accommodating the ore-bearing bodies in the O'okiep area, are largely of this generation of shear zones only because those which were seen during the survey had the same direction of strike.

3. The third episode (F_7)

The most profound brittle fracturing of the Namaqualand gneisses was initiated during the third episode of the second event of deformation and movements along lines of structural weakness brought about by this episode continued with interruptions until after the deposition of the Nama sediments. There are indications that movement along these mainly north-south lines of weakness may have been synchronous with or even predated the earlier episodes of shearing, but by and large, the prevailing evidence indicates that the order as suggested here is correct.

The effects of north-south fracturing are only too evident in all parts of the area as can clearly be seen in the maps of the eastern part of the area. The area is transected by numerous faults and wide zones of closely-spaced joints, usually seen in the field as wide reddish-coloured belts traversing the country. Even under the microscope the effects of this fracturing are noticeable and hardly a thin section was examined which did not have small fractures attributable to this episode.

The evidence indicates that the earliest and largest north-south movements took place in a zone along and to the west of the escarpment on the eastern side of the strip of maps in the west and it is thought that the movements originated what is today seen as a scarp. To the south the escarpment is almost absent, but the same type and strike of deformation is still apparent in the western part of the area.

Apart from the faults and joints to be described later, the deformation is manifested in several ways. It has features in common with the shear zones described above and the main distinguishing feature is the constant northerly direction, usually slightly to the west of north. Closely-spaced cleavage traces, marked by thin lines of recrystallisation and causing crenulations in the foliation, are common (Plate XXIII). In the coastal area small north-northwest subsidiary shear zones are seen branching away from the main north-south shears, especially common in the area covered by sheet 2917CB, and this is a shear direction which became prominent only after the deposition of the Stinkfontein Formation.

Plate XXIII. Deformation by movement along north-south planes of slip, Stryd River

Mylonites along lines of dislocation with left-lateral horizontal displacement are fairly common over most of the area, but many of them have been overtaken by later faulting along the same line. The zones of shearing have accomplished complete crushing in places where porphyroblastic gneisses have been affected and schistose rocks devoid of porphyroblasts have been formed. Refoliation with the development of new biotite, especially pronounced along the escarpment, was seen in a number of places, while at Bontekoe and along the Kamaggas River (2917B), new banding has developed as fine leucocratic bands traversing the mafic rocks there.

The shear zones, varying in width from less than one centimetre to almost 0.25 km, and accompanying cleavage and mylonites are usually vertical or nearly vertical with perhaps a greater tendency to dip steeply to the west, but at Dikmatje (3018AB) a shear zone with a dip of 40 degrees to the east was encountered. In the coastal area several shear zones were found dipping moderately to the west and at Brazil on the coast and south of the present area, a tectonic schist containing remnants of augen as felspar nodules was seen to dip 25 degrees to the west while maintaining the northerly strike. On Nakanas (2917AC) the original banding in the quartzites was completely destroyed by the development of new banding parallel to north-south planes of slip. On Soetwater (2917AB) small silicified zones formed and they consist of numerous small anastomosing veinlets of milky quartz, all roughly aligned north-south. In places these siliceous zones are indistinguishable from the quartzites normally occurring in the sequence. On Langedam (3018CD) the quartzite forming the ridge on which the trigonometrical beacon of Spitskop is situated, has been investigated by Brink (1950, p.112-113), and contrary to expectation, the hill was found to consist mostly of cataclasites in the form of much-fractured quartzite and numerous veins of quartz. The sheared conglomerate mentioned by Brink could not be found and perhaps he referred to the nodules of milky quartz produced tectonically.

Phyllonites which are so commonly associated with the later phases of deformation were first produced by the north-south episode. These rock types are found in a number of places at the foot of the escarpment and to the south at Rietpoort (3018CC), and as they are soft and easily eroded, the phyllonites crop out intermittently along the trenches formed along the zones. They can never be followed for long distances along strike, but are certain to continue for many kilometres. The best example of a phyllonite formed along a shear zone was found between Nuttabooi and Komaggas (2917CB) where the highly sheared mafic rocks also contain large white quartzose discoid phacoliths (Plate XXIV) derived from the attenuation and disjunction of quartz veins emplaced along the zone.

Horizontal and vertical displacement could only be measured

Plate XXIV. Quartz phacoliths in a north-south zone of phyllonite, Nuttabooi

in the smaller north-south shear zones and in nearly all cases the horizontal displacement was left-lateral (Fig. 46) and where vertical displacement could be determined, downthrow was on the western side. Occasionally contrary displacements were encountered. A small shear on Dikmatje (3018AB) has right-lateral horizontal displacement which was also the case in a minor shear along the Komaggas River where a contrary vertical displacement is also evident. The horizontal displacement is usually relatively small; a mylonite about three metres wide has sinistral displacement of only five metres (Rietfontein; 2918CC).

All shear zones show some drag of the pre-existing foliation along their margins and in exceptional cases, curvature through almost 90 degrees was recorded. Mild folds with gentle plunges to the north were measured in several places on the coastal flats, but similar folds almost certainly exist in the eastern parts of the area and could only be proved by more detailed work. The mild fold across Menschlief Hill (Lennies Kraal; 3018CD) can possibly be ascribed to a fold of this generation. Between Nanassen and Nana (2917AB) north-south trending monoclinal folds, less than one metre from limb to limb, and with their steep shorter limb to the west, plunge from 25 to 35 degrees to the north. The rocks, even quartzites, are much crenulated along zones of shearing and larger folds with axial planes concordant with those of the crenulations formed (Plate XXV). In two localities very tight folds were encountered. The shear zone across Roodevlei beacon hill (2917CA) shows mild curvature along its eastern margin (Fig. 47), but extremely tight folding within the zone (Plate XXVI) as well as folds belonging to earlier phases of deformation dragged parallel to its strike. On Witkoppie (2917AD) a north-northwesterly branch to a north-south shear zone contains a quartz vein with some epidote and is accompanied by a mild marginal fold plunging 40 degrees to the north-northwest.

Lineations, consistent with those of shear zones described before, usually plunge steeply to the north, but two southerly plunges were recorded in mylonites in the eastern part of the area. When the shear zones dip either east or west, the plunge of lineations naturally conforms. A shear zone on Soetwater (2917AB) changes direction from due north-south to ten degrees west of north while at the same time the dip changes from vertical to 55 degrees east. The lineation alters its direction from steep north to about 50 degrees to the north-east.

Thin acidic veins, usually fine-grained but in places coarsely pegmatitic, have also been emplaced along the fracture zones of this phase of deformation. In some localities they occur along fractures displacing the older pegmatites. Quartz veins are also found along the zones and at Oograbies (2917AA) are associated with minor amounts of copper. On Soetwater the pegmatites and quartz veins were seen to become attenuated and disjointed and the fragments refolded by continued movement. These phacoidal fragments are in some places strongly rodded in the direction of the lineation. Mafic dykes have been intruded along the north-south fractures and like some of the pegmatites, have become sheared since their emplacement.

Several specimens collected along the north-south fracture zones were examined under the microscope. The rock collected in the shear zone due south of the village of Komaggas is a greyish brown, finely crystalline rock with lenticular aggregates of fine red garnets. It consists of pale brown biotite and diablastic pinkish garnet in a granoblastic matrix of quartz. The biotite has sagenitic webs, imparts a strong foliation to the rock and is associated with a small amount of some fibrous mineral.

The phyllonite from between Nuttabooi and Komaggas mentioned above, is a fine dark, brownish grey, shimmering schist and in thin section is seen to consist of greenish blue amphibole, greenish biotite and thin bands of finely granulated quartz. Quartz also occurs in coarser grained lenticles about which the darker bands are curved. Altered felspar occurs in the lenticles of

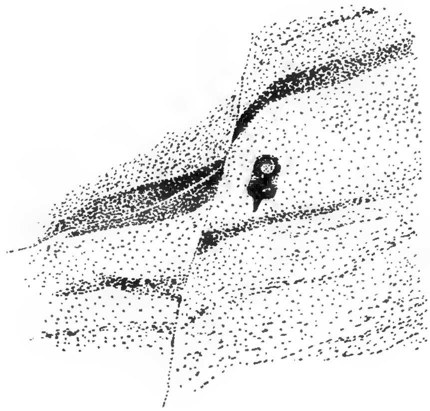


Fig. 46. Left-lateral displacement along minor north-south fracture

Plate XXV. Folded quartzite along north-south shear zone, Nanassen

Fig. 47. Curved layering along the edge of the north-south shear zone, Roodevlei

Plate XXVI. Tightly folded layer of quartzite in the north-south shear zone, Roodevlei quartz and contains numerous small grains of epidote arranged in parallel lines while quartz is clear, showing only thin lines of granulation. Epidote is also present with the amphibole and biotite as numerous small grains while some lenticles of crushed ore and small crystals of apatite are the other accessory minerals.

A quartzitic rock found on the southern side of Breekhoorn Hill (2917AC) has the appearance of a coarse grit, but on closer examination can be seen to have fine north-south fractures across the banding and is almost refoliated. In thin section it is seen to consist of a coarse mosaic of strained quartz. Part of the thin section reveals fractures filled with brown opalescent chalcedony and here the quartz is finer grained. Another set of younger fractures, similar in all respects to those described above but at right angles to them, also transects the rock. The rock is thus the result of fracturing parallel to F_3 followed by north-south cleaving dividing the specimen into blocks and the assemblage resembles a grit in hand specimen.

Many specimens examined in thin section reveal fractures across the felspars where epidote and calcite appear. In some cases sericite is found along the fractures and in other rocks tiny veinlets composed of a mosaic of unstrained quartz traverse the rock parallel to the fractures. In many of the rocks muscovite is prominent and is seen forming bands alternating with ribbons of quartz. Where biotite is present it is most often green due to alteration, while felspar is densely altered or displays peripheral sericitisation. Sphene occurs in one specimen as crushed grains along a plane of slip which curves around the larger grains of sphene. In another specimen chlorite is present instead of biotite and here the iron ore is granulated.

4. Rejuvenation of movement along north-south fractures

There are many localities where it can be proved that north-south trending folds and deformation followed on the deformation of the Stinkfontein Formation and that repetition of movement along these lines took place at a later stage.

The most convincing proof was found on Drooge Kraal (2917AC) where the lamination and the associated lineation brought about by shearing during the phase of deformation subsequent to F_7 are mildly folded about north-south trending axes (Plate XXVII). On Steenbok (2917AC) isoclinal folds of the F_2 generation are mildly folded in a north-northeast direction by the phase mainly responsible for the deformation of the Stinkfontein Formation and subsequently crenulated in a north-south direction, while on Tusschen In (2917AB) the axial planes of folds trending north-northeast are mildly curved about a north-south direction. Similar examples of mild curvature as well as crenulation in a north-south direction

Plate XXVII. Laminated rocks along north-northeast shear zone refolded in a north-south direction, Kaavlakte

of the foliation of phyllonites in north-northeast belts, are seen in a number of places in the north-western part of the area. Furthermore, the pegmatites associated with the north-northeasterly shear belt in the Tussenin Hills tend to be irregular ramifying bodies and they were subsequently transected by north-south, regular lenticular pegmatites. Similarly, north-south fracturing of granites which appear to have been emplaced towards the close of the main deformation of the Stinkfontein Formation, indicates rejuvenation of movement along these lines of structural weakness.

5. Metamorphism during the second event

As deformation during the second event is mainly confined to shear zones, the gneisses were metamorphosed only along narrow belts during this stage of their development.

The mineral assemblages (quartz-biotite-garnet-plagioclase ±muscovite; quartz-microcline-biotite-plagioclase±muscovite;

hornblende-plagioclase-garnet-biotite; hornblende-plagioclase-biotite-epidote) found along the shear zones in the eastern part of the area are typical of the almandine zone of the Scottish Highlands and indicative of amphibolite facies metamorphism. Towards the escarpment the assemblages are transitional between the greenschist and amphibolite facies as described by Turner (1968, p.309), while in the west greenschist facies assemblages (muscovite-chlorite- quartz) become increasingly more prevalent. However, in view of the rejuvenation of movement, more detailed work is required to confirm whether the lower grade of metamorphism nearer the coast is not mainly due to subsequent deformation.

6. The age of the second event

There can be no doubt that the deformation during the second event, apart from later rejuvenation, preceded the main phase of deformation of the Stinkfontein Formation and that it followed on the last episode of the first event of deformation. North-south fractures filled with ferruginous material at the base of the Nama sediments at Polly's Kloof (2917DC) prove that these movements originated before ±600 My.

As mentioned before, the trough receiving the sediments of the basal part of the Stinkfontein Formation must have had its longer dimension in a north-south direction and subsidence was probably initiated towards the end of the second event. It will also become clear from the description of the subsequent deformation that the second event happened largely prior to the deposition of the Stinkfontein Formation and the emplacement of the majority of mafic dykes in the coastal area.

By reasoning and by employing the scant isotopic dates available, it is possible to arrive at some indication as to the age of this phase of deformation. Hugo (1965, p.189) has suggested that there are two ages of pegmatites; those of the 1,000 My age (emplaced along fractures of the F_4 deformation as suggested before), and those ranging in age from 937±30 to 890±30 My. If the later pegmatites, other than the segregation pegmatites occurring along shear zones, are present in Namaqualand south of the belt of 1,000 My pegmatites, they must be those consistently found along north-south fractures also mentioned by Benedict et al. (1964, p.761). It would thus appear that an age of approximately 900 My, which would be in accord with the ages suggested for the episodes before and after this event, could be assigned to the final episode of the second event.

E. THE THIRD EVENT

1. General description of deformation (F_8)

The rocks on the coastal flats have been severely deformed by many major and numerous minor vertical shear zones striking in a north-northeasterly direction, with the result that the existing foliations and folds have been deformed and refolded in a great variety of styles. Although minor crenulations in a north-northeasterly direction are found in the eastern part of the area as described before, deformation along lines trending in that direction only becomes prominent a few km east of Komaggas. The evidence for stronger movement in a north-northeast direction was first seen in the crenulation of augen gneisses some five kilometres south of Biesies trigonometrical beacon (2917 DC; Fig. 48), while in the hills of Komaggas fairly large folds, more than one kilometre from limb to limb and plunging gently north, appear folding the quartzites. A major shear zone striking in a north-northeast direction was first encountered in the Kanfontein Hills (2917CB) to the north of Komaggas where the rocks have been converted to soft plyllonites and in the same area, minor shear zones and associated folds become the most prominent deformation. Deformation along lines in the same direction is common from the escarpment all the way to the coast and in many places the banding is completely obliterated and all traces of earlier folds destroyed.

The shear zones and planes of refoliation are nearly always vertical or very steep, but in a very few places small shear zones of this generation dipping moderately to the west are encountered. In one case, at Oograbies (2917AA), a shear measured on surface as dipping east was found to be misleading as the curvature of the subhorizontal foliation into a vertical shear zone was the only indication on surface.

Thin recrystallised leucocratic lines mark the position of planes along which slip took place, but they rarely become so prominent as to result in new banding in a north-northeast direction as in the case of the earlier shear zones. The rocks produced by shearing are usually silvery phyllonites and all stages between unsheared rocks and phyllonites are encountered. The effects of shearing are first seen as strong jointing in the gneisses giving way to thin discontinuous lines and in some places streaks of leucocratic material with clusters of dark minerals produce rude banding across the pre-existing foliation. Nearer the shear zone the rocks become flaggy with shimmering foliation surfaces and the contact of the shear zone where the phyllonites are developed is generally sharp. On Hardevlakte (2917AB) an interesting set of small en echelon shear zones, each individually striking in a north-northeast direction, lies along a zone in a north-eastern direction.

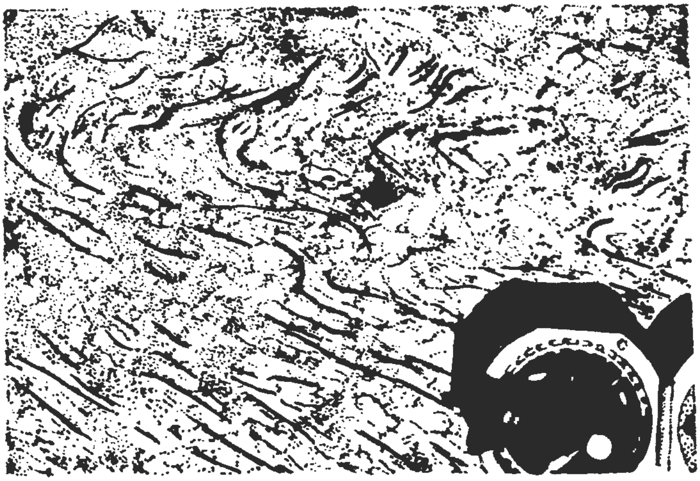


Fig. 48. Crenulations in augen gneiss, Biesies

Under the microscope the effects of shearing are well demonstrated. The first signs appear in the development of sericite mantling the felspar and eventually forming patches in the matrix (Fig. 49). These patches become elongated and more streaky until they form continuous bands enclosing lenticular relics mainly composed of quartz, but in some specimens with biotite still orientated along the inherited foliation (Fig. 50). In the phyllonites the rocks consist of alternating bands of well-orientated flakes of muscovite and crushed quartz grains. In the axial planes of minor folds accompanying the shear zones a new generation of muscovite is formed (Fig. 51).

The horizontal displacement along the largest shear zones could not be determined, but in all the others where the affected zones do not assume major proportions, the displacement was left-lateral. Only two cases amongst hundreds of shear zones were recorded as having right-lateral displacement.

The inherited foliation can be seen to change in dip and strike on approaching a shear zone, resulting in mild marginal curvature in the proximity of the zone. The resultant folds are mild open structures and, in accordance with the nature of folds associated with shear zones, become more tightly appressed along the borders of the shear zone and also plunge more steeply. In places folding resembling ptygmatic folding results on the edge of the shear zone (Plate XXVIII). The mild open folds are almost

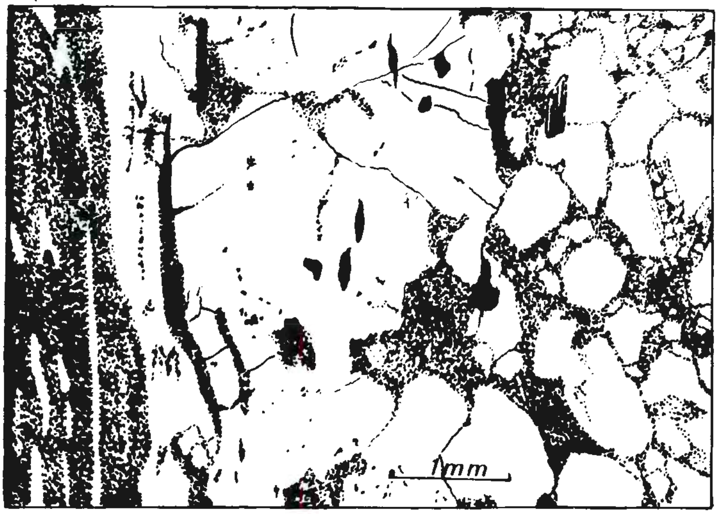


Fig. 49. Sericite bordering on felspar and forming patches along the edge of a shear zone on Stygerkraal

Fig. 50. Lens of unaltered rock with inherited foliation in phyllonite at Nana (x50)

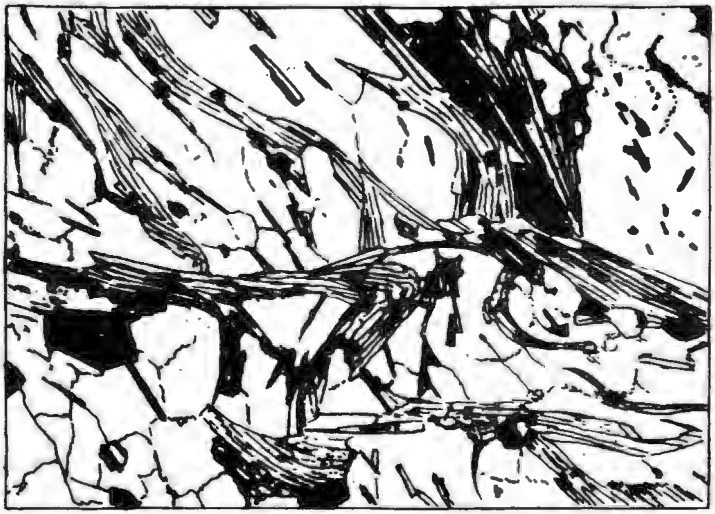


Fig. 51. Folding of biotite muscovite-quartz schists with new muscovite formed along the planes of slip, Haouseep (x50)

Plate XXVIII. Tight folding along the edge of a major shear zone, Tusschen In symmetrical in some localities, but are usually asymmetrical and where monoclinal folds are found, they have their shorter limb to the east. In a shear zone at Bontekoe (2917CB) the associated folding produced well-developed kink-banding, but crenulations brought about by movement along closely-spaced planes of slip are common, while transposition structures, so common in the earlier phases of shearing, are only occasionally encountered.

Pegmatitic stringers along the axial-planar cleavage of the marginal folds become more prominent on approaching a major shear zone. In the shear zones several phases of pegmatite and granite emplacement can be recognised. Granitic and pegmatitic material is commonly found sheared in various degrees of intensity and these have been intruded by later acid rocks in the form of large ramifying and cross-cutting, unsheared granitic bodies. Emplacement of granite thus appears to have occurred even during the closing stages of the deformation. The emplacement of later acid bodies resulted in the bulging of phyllonites, now showing variable dips and strike of foliation at the contacts. As in the case of the older shear zones, quartz veins are of frequent occurrence along the major shear zones and these are emplaced roughly parallel to the foliation of the phyllonites. In places the quartz veins show swelling in the shape of thickened pods elongated parallel to the lineation in the phyllonites and have been seen to become attenuated and disjointed so that only phacoids of the quartz veins remain in the phyllonites. The remnants of the quartz veins also form tight folds, appearing to indicate continued movement since the emplacement and attenuation of the quartz veins.

The strong lineation associated with the shearing is seen as elongated mineral clusters and rodding and fluting of quartzites. While the lineation in the marginal folds is formed by the intersection of the existing foliation and the newly-developed planes of refoliation, it plunges gently, usually to the north, but the lineation in the shear zones plunges steeply down the dip, almost vertically, and is in most areas mildly curved. In the zones of strong shearing where the closely-spaced planes of slip produced paper-thin laminations or even foliae, the lineations are seen to vary slightly in angle of plunge from one slip plane to the next. As in the case of the tight folds in the shear zones, the plunge of the lineation in many places is seen to steepen in depth.

Some of the shear zones display some copper mineralisation which is in some places associated with quartz veins while at the most important occurrence at Steenbok (2917AC), the copper is associated with sheared mafic rocks. Ferruginous zones occur in a number of places and lepidolite is found in a pegmatite emplacement along a north-northeast shear zone at Soetwater (2917AB).

The largest shear zone of this phase of deformation traverses the area from Drooge Kraal (2917AD) in a north-northeasterly direction across Steenbok to Nana and Grasvlakte (2917AB) and from there in a north-northwesterly direction to the northern border of the present area. From there it can be traced again in a north-northeasterly direction into the Richtersveld area where it was mapped by de Villiers and Söhnge (1959) as a light-coloured sericite schist.

The change in strike of the shear zone is in agreement with the nature of the F_8 deformation which, in a number of places, is seen to consist of a conjugate set of folds with minor north-northwest trending folds complementary to the main north-northeast shear and fold direction. The north-northwest folds are not well-developed in the gneisses, but are fairly common in the rocks of the Stinkfontein Formation (Joubert and Kröner, in the press). Strong north-northwest kink-banding can be seen in the rocks of the Stinkfontein Formation at Wolfberg beacons (2917CA), and on the farm Vredefontein (2917AA) the almost box-like folds resulting from the synchronous deformation in two directions are shown (Plate XXIX) as well as later phases of deformation clearly recorded in the finely laminated rocks.

Plate XXIX. Conjugate folds (F_8), subsequently mildly deformed by movement in a north-south direction (parallel to the compass) and jointed in a west-northwest direction

South of Drooge Kraal the main shear zone is not exposed, but on that farm the effects are mainly seen in the deformation of quartzites. A phyllonite zone starts to the north-east of Drooge Kraal beacon and its contact with almost undeformed rocks to the east is sharp. Thin, highly contorted quartzites appear edging the phyllonite zone farther north, while the quartzo-felspathic rocks to the west of the phyllonite also crop out as flags due to the development of closely-spaced planes of slip in them. Farther west and against the next quartzite ridge there, a thin zone of strong shearing is again evident and this only becomes wide enough to be mapped north of the Port Nolloth-Steinkopf road. The main phyllonite zone branches on the farm Aardvark with the westerly branch cutting across to Nana where it joins the above-mentioned zone, while the other continues to the north-northeast and eventually disappears under the soil cover. At Nana the shear zone again has thin contorted quartzites associated with the phyllonites and they can be followed, with a break on Grasvlakte, to the hills of Tusschen In, where the change of strike to the north-northwest is marked by the prominent ridges of quartzite (Plate XIV). Farther north smaller shear zones striking to the north and northeast branch out from the main north-northwest zone. It may be argued that some of the quartzites represent silicification along the shear zone similar to those described in the earlier phases of folding, but the quartzites here are much thicker than those described before and the quartzites at the northern extremity of the Tussenin Hills on Chabiesies have members typical in appearand to the ferruginous quartzites found in the normal sequence of the metasediments. Steeply plunging almost isoclinal folds occur all along the shear zone (Fig. 52), and are most easily recognised when the quartzites are folded. The folding of the rocks along the main shear zone and along its margins is also clearly displayed on the map.

In one locality along the main shear zone the foliation and lineation are both curved by "bulging" in the foliation planes. The mild welt-like bulges are horizontally disposed and are associated with subhorizontal fractures. In two places, below Tussenin trigonometrical beacon and west of Nana trigonometrical beacon, slip along horizontal or gently north-dipping planes caused crenulating of the phyllonites (Plates XXX and XXXI) so that sigmoidal folding of the recrystallisation lineation resulted. The kinking did not affect the more competent quartzite which still shows the original steep lineation and in one locality west of Tussenin beacon, apparent repetition of slip along vertical planes gave rise to the mild curving of the subhorizontal planes of slip.

The geometry and symmetry of similar secondary crenulation in kink-bands occurring in the western Asturias of north-west Spain have been described by Matte (1969). As in the present area, the kink-bands are localised in narrow schistose zones in contact with competent quartzitic rocks, but in Namaqualand they appear to have been most strongly developed in areas where changes in

Fig. 52. Tight fold in quartzites and phyllonites along major shear, hillside on Chabiesies

Plate XXX. Crenulated phyllonite at Tussenin Beacon

Plate XXXI. Rodding of quartzite parallel to lineation in shear zone and not distorted by crenulations in phyllonite, Tussenin beacon

strike of shearing occur. The schists are described as being connected with normal faulting and the kink-bands are explained as resulting from horizontal extension across the foliation formed under nearly vertical compressive stress. It is suggested that the stress in Spain is the result of the lithostatic load during a late phase of deformation when the orogenic forces relaxed. In the present area there is no doubt that the superposed horizontal cleavage took place during a late stage of the deformation as tight folds and the associated steep lineation in the shear zone were deformed, but as recorded above, were succeeded by minor rejuvenation of vertical shearing. The kinking can also be seen in thin section (Fig. 53) and in places distorting the lenses of quartz between the strongly foliated bands.

The kink-bands are of the type described by Dewey (1965) as shear kink-bands developed by continuous simple shear on an invariant axial-surface.

Fig. 53. Crenulations in phyllonite, Tusschen In (x50)

Deformation of the vertical shear foliation appears to have been caused by pulsating movements so that even the newly-developed foliation planes were crumpled to form tight folds, but is generally seen only as mild curvature in the foliation of the phyllonites plunging in the same direction as the lineation. It would appear that, in the present area, all the structural features seen along the shear zones can be correlated with one episode of deformation except for minor structures which are without doubt related to later phases described below.

The refolding of older folds and their attenuation along the shear zones are evident in a number of places and can even be seen under the microscope. Subsequent deformation by repeated movement along existing lines of weakness of earlier phases of deformation, has resulted in the distortion of the phyllonites. Mild folds, described and illustrated in the previous section, distort the newly-developed foliation and the effects of translation along north-south lines of weakness have also been found in thin section. On the farm Steenbok a good example of an isoclinal fold, refolded mildly in a north-northeasterly direction and subsequently crenulated by north-south closely-spaced planes of slip, illustrates the structural features of the area.

North-east of Komaggas a flaggy outcrop of micaceous phyllonite derived from the shearing of the gneisses there, swings abruptly in strike from a north-northeasterly direction to a pre-existing north-easterly shear zone of an earlier phase of deformation where a higher grade of metamorphism is evident farther along the strike; rejuvenation of movement along this line of dislocation took place during the deformational phase of F_8. On the northern side of Steenbok the main shear zone has many complementary fractures in a north-eastern direction and in the Tussenin Hills, similar fractures are accompanied by upright folding of the phyllonites, but the folds can only be followed along their trends for distances of a few metres.

The shearing at the base of the Stinkfontein Formation has been adequately described by Rogers (1915, p.84) and further details are recorded under the discussion of those rocks here. The main phase of folding of the Stinkfontein Formation and the gravitational sliding of the sediments into the trough from the ridges originating by differential vertical movements in the floor, is ascribed to the F_8 episode of deformation. The folds in the Stinkfontein Formation plunging either south-southwest, north-northeast or north-northwest reflect the conjugate nature of the deformation. While the main folds most commonly trend north-northeast as illustrated by Rouffaer (1965, p.66, Plate III), north-northwest trending folds are common on the western side of the hills at Springbokvlei trigonometrical beacon (2917AA) and Kwakanab (2917AC) as well as the kink-bands mentioned above.

An excellent example of the way in which the deformation of the Stinkfontein Formation could have been accomplished, is suggested by the experiments conducted on structural models by Tanner (1962) and seems to fit the structural setting of these sediments admirably. He has found that, even though only horizontal displacement was impressed on the "basement", considerable vertical adjustment in the "cover rocks" was obtained and that the surface effects were mainly expressed in vertical movements, resulting in horst-and-graben chains which were end-to-end rather than side-by-side. In the models the horsts tended to have their longer dimensions parallel to the strike-slip direction of the movement in the basement while the orientation of the graben was slightly off-set. These features are strikingly similar to the structural setting of the Stinkfontein Formation, with the high ground formed by the Oograbies and Lekkersing Hills and the intervening trough at a slight angle, in which rocks of the upper part of the formation overlap across the basal quartzites onto their basement. The gentle curving line of the faulted contact in the north can be compared with the undulatory fault-lines of the models and the areas of gravitational sliding as suggested by the models are in agreement with the location of regions where folds, which could only have been produced by gravitational sliding, are found.

The sheared rocks of this phase show various degrees of deformation, and the final products along the shear belts are highly schistose rocks. They are usually silvery white schists, but are also grey, greyish brown, yellowish and even green in those specimens containing a fair proportion of chlorite. The stages of shearing are amply displayed in the many examples examined microscopically. As mentioned above, the first indications of shearing are noticed in the development of sericite around felspar crystals and patches of sericite form at the expense of the felspar. The sericite patches become elongated while quartz, and even garnet when present, become cracked. Thin threads of sericite travers the rocks and these lines are at first not straight, but tend to bifurcate and anastomose around lenticles of unaltered rock; in most cases they are iron stained. All felspars disappear eventually and the slip zones become pronounced producing strong banding around small lenticles of quartz, with flakes of muscovite or chlorite aligned along the direction of the inherited foliation in some rocks. Coarse flakes of muscovite develop and even form around small folds and along the direction of their axial planes, but the individual flakes are not bent. Biotite is present in a number of these rocks as lenticular aggregates and can be seen to become bleached with concomitant separation of ferruginous pellets along the cleavage traces or, more rarely, it becomes chloritised. Quartz usually appears forming lenticular aggregates between the bands of sericite, but also occurs as scattered angular grains in the sericitic groundmass; the grains are usually somewhat rounded and tend to be equidimensional.

Chlorite is patchily distributed and in one rock the enclosed sagenitic webs indicate that it has been derived from biotite. Chlorite formed during this episode of deformation, but the bent flakes as well as flakes of chlorite orientated along the inherited foliation appear to indicate that the mineral was in existence prior to, or developed at an early stage of, this phase of deformation.

Iron ore is crushed along the lines of movement and the banding in many of the rocks is of a reddish-brown colour even in hand-specimen. In a number of the phyllonites the quartz lenticles contain ore which appears to have been recrystallised and is now seen as euhedral to subhedral crystals, a feature not seen elsewhere in the rocks examined microscopically. Where seen, sphene is usually crushed, but in one speciment fairly obvious lozenge-shaped crystals occur, while the few small crystals of apatite and zircon seen in some of these rocks appear to have escaped alteration. Calcite as well as epidote, in one case with cores of piedmontite, occur in a few of the phyllonites.

In two specimens plagioclase, apparently of a second generation, is present while in two other phyllonites small brown metacrysts of chloritoid appear. In the specimen from west of Nana beacon the foliation is curved around the metacrysts and in the phyllonite from north-east of Witbergkloof beacon the poikiloblastic prisms of chloritoid have crystallised across the foliation (Fig. 54).

The crenulations illustrated above (Fig. 53) in some cases have the appearance of chevron folds, but the planes are not always parallel neither are they continuous. In these crenulations the individual flakes of muscovite become highly folded as illustrated and a new generation of muscovite can also be seen to have formed along the axial planes of the folds.

Repetition of north-south shearing of the phyllonites is seen in a rock collected in the north-eastern corner of the western part of the area. Here the lines of slip between which the phyllonitic foliation is curved, are marked by thin dense, ferruginous zones, in places tending to follow the direction of foliation of the phyllonites (Fig. 55).

An interesting thin section was prepared from a rock collected at Grace's Puts (2917CB) where the refoliation was superposed at right angles to the existing foliation and banding, resulting in a checkerboard structure. Biotite flakes which are still orientated along the inherited foliation have been severed, with only slight disturbance, along slip planes of the newly-developed foliation. The new foliation is not pronounced and is rather irregular, but flakes of muscovite formed along these new planes of slip.

The general swing in the strike of the banding in the Namaqualand gneisses from east-west to north-northeast as the coast is approached was first recorded by Rogers (1904, p.22) and as mentioned before, is most pronounced in the area west of Bitterfontein to the south-west of the present area. The curvature of the banding can be ascribed to large-scale sinistral movement to the west of the escarpment and although the movement was initiated during the earlier phases of shear deformation, the change in

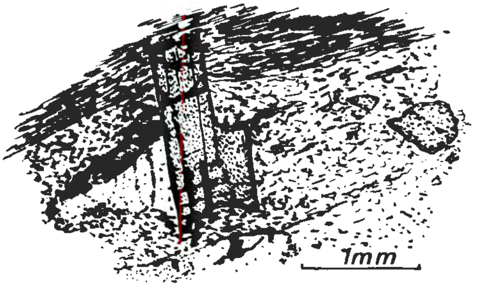


Fig. 54. Metacryst of chloritoid lying across the foliation of phyllonite, Styger Kraal

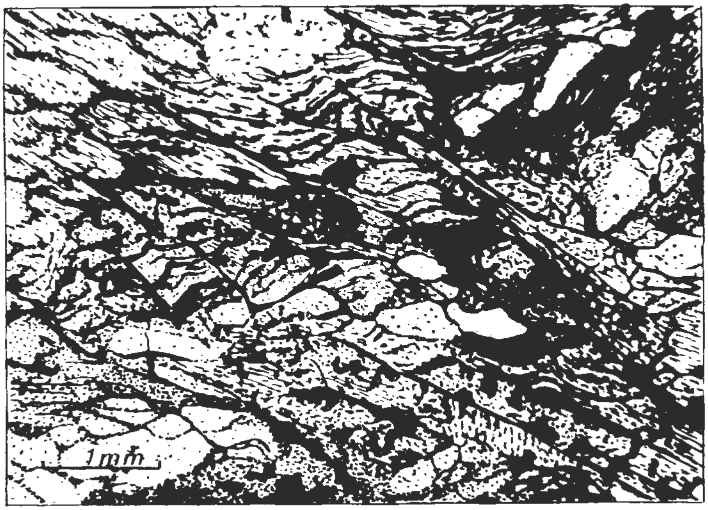


Fig. 55. North-south refoliation of north-northeast phyllonite zone, Chabiesies

strike must have largely been accomplished during the third event of deformation. Wherever the displacement could be measured along the north-northeast shear zones a sinistral movement was found to be prevalent and drag in the foliation and banding sympathetic to the large-scale curvature was recognised.

De Villiers and Söhnge (1959, p.201) record the presence of folds trending nearly north-south in the Richtersveld and in the southern parts the trend of the folds swings to the north-east. The map of the Richtersveld also shows quartz-sericite schists at the base of the Stinkfontein Formation as well as in a zone between Stinkfontein and Rooiberg and these all appear to be related to this stage of deformation, while the presence of sillimanite there could possibly be ascribed to metamorphism associated with the Rooiberg Igneous Complex.

The shear belts associated with the deformation during the third event, with less obvious exceptions, consistently strike to the north-northeast, but to the east of the escarpment, the effects of this deformation are minimal. However, north of Prieska the same direction can again be seen in the distribution of the Matsap sediments of the Ezel Rand and in the extension farther to the north in the Lange Bergen (Geological map of the Marydale area, Sheet 40, Geol. Comm., C.G.H. 1910). A large north-south trending open synform farther east deforms the sediments of the Transvaal System and an anticline with a similar trend appears to effect the swing in the line of Matsap rocks where they cross the Orange

River. Although these areas have not been remapped, similar structures, not apparent on the map, occur in the rocks of Kheis age farther south (personal observation). It would appear that folds with similar trends to those of the third event deform the rocks on the eastern side of the area of high-grade M_2 metamorphism and it may be suggested that similar tectonic events took place in those regions. However, the cover rocks affected by the tectonism there are of much greater antiquity than those in the west, the age of the Transvaal sediments being accepted as being ±2000 My (c.f. Nicolaysen et al., 1958), and it is possible that the deformation antedates that of the coastal area. Johnson (1969) remarked on the possibility of migration of folding or migratory fronts of plasticity within an orogen and concluded that folding deformed the whole orogenic belt at the same time, although not necessarily with the same intensity. Polyphase deformation implies a series of pulsatory stresses interspersed by tranquil periods, and the indications are that a phase of deformation and metamorphism could have extended over a period of scores of millions of years or could have happened rapidly.

The folds and lineations in the post-gneiss beds north-west of the Salt River mouth in the area to the south are illustrated by Kröner (1968, Figs. 38, 40) and are comparable in direction of plunge with the folds in the Stinkfontein Formation with which these rocks can be correlated (Dr. A. Kröner, personal communication).

2. Metamorphism during the third event

It is clear that the phyllonites of the third event were developed under conditions yielding mineral assemblages of the greenschist facies of metamorphism and according to Winkler (1967, p.98-101) could be grouped in the quartz-albite-epidote-biotite subfacies. Winkler (op. cit., p.22) took the presence of chloritoid as a positive criterion of greenschist facies metamorphism, but mentioned that this mineral can form at low pressures only when a very particular bulk chemical composition is realised (p.92 and 94-95). Harker (1939, p.213, Fig. 95b) illustrated a chloritoid-sericite schist which is very similar to the specimen collected near Witbergkloof beacon and mentioned that in rocks with an abundance of alumina, sufficient iron oxide and poor in magnesium, lime and potash, chloritoid forms readily and persists through a wide range of temperatures. Atkinson (1956) concluded "that a very close connection exists between the incidence of intense movements and the development of chloritoid as the mineral is in many cases limited to a zone only a few tens of feet wide which is demonstrably a zone of dislocation" in the Hecla Hoek Formation where the appearance of this mineral is similar to the occurrence in the present area. He also stated that the growth of chloritoid was contemporary with the deformation. This certainly appears to be the case of one of the occurrences in the present area where the chloritoid metacrysts lie in the foliation planes, but in the other instance as illustrated (Fig. 54) the mineral has crystallised across the foliation and has possibly been generated at a later stage. Halferdahl (1961) reviewed the literature on the occurrences of chloritoid and came to the conclusion that this mineral can be present, amongst others, in some rocks which have undergone both regional and contact metamorphism. It seems possible that this may be the case with the chloritoid occurrences here.

Other indications of a thermal event in the coastal areas towards the close of the third event of deformation, have been mentioned before and are thought to be connected with the emplacement of granites, tentatively correlated with the Richtersveld granite (De Villiers and Söhnge, 1959). The staurolite crystals, in places lying across the foliation as well as those with dense cores surrounded by clear mantles, indicate that this mineral formed and existing crystals increased in size during a later stage than those of the M_2 deformation. Similarly, the occurrence of garnet in the mafic dykes emplaced during this phase of deformation signify a thermal event following on the main stage of the deformation. That a recurrence of movement took place since the generation of garnet is indicated by the sheared specimens of the garnetiferous dykes in which the garnets are cracked and in some specimens rimmed by chlorite. It therefore appears that the granites were intruded towards the close of the major stage of the third event (F_8) and that minor movement followed on their emplacement.

Furthermore, the zone of disharmonic folding (Plate VI) in the gneisses seen in the south in places from the Buffels River, at Meidjes Karroo and farther north as mentioned before, appears to have been effected when the gneisses became more plastic and could possibly be ascribed to a thermal event at this stage.

3. The age of the deformation

The north-northeasterly shear zones constitute lines of structural weakness along which numerous mafic dykes have been intruded. That these dykes are closely associated with the deformation during the third event is apparent in their strike and in the sheared nature of the majority of them. One of these dykes has been dated as 878 ± 41 My (De Villiers, 1968, p.35) and, as has been pointed out above, some of the dykes occurring along a north-south zone are garnetiferous and together with the other indications mentioned above, appear to indicate the effects of a thermal event towards the close of this phase of deformation. It would appear that the only source of thermal metamorphism could only have been connected with the intrusion of the "younger" granites during this stage of events and as mentioned above, the granites are correlated with the Richtersveld granite dated at 850±20 My (De Villiers and Burger, 1967). The fact that the dykes have been sheared, that they have had garnet generated in them and that they traverse the Richtersveld granite (De Villiers and Söhnge, 1959) prove a lengthy history of dyke emplacement. As recorded before, the first north-south movements appear to have taken place about 900 My ago; the ages indicated by the dykes and granite for this deformation are in agreement with the dates assigned to earlier and later events. If the age of the Lower Nama beds is not younger than ±600 My (Martin, 1965, p.116) then the deformation of the third event must be older as those sediments were not disturbed and therefore not deposited at that time.

The north-northeasterly trending shear belts and associated folding in the present area are clearly part of a deformation on a regional scale along the coast and its effects must have been recorded elsewhere. The extensive phase of deformation similar to that seen in the Stinkfontein Formation is that of the Damara which Clifford (1967) recorded, apart from the north-east trending segment from the coast inland, as a continuous roughly north-south zone along the coast of South West Africa. However, the general range of radiometric ages is recorded as 450-550 My and is younger than those indicated for the event in the present area. Guj (1970) noted that, in the Kaokoveld where the structure, the history as well as the lithology of the Nosib Formation are remarkably like those of the Stinkfontein Formation, the first deformation was unlikely to have occurred later than 600-700 My ago and compared it with the Katangan episode recorded by Clifford (op. cit., p.5) as yielding ages of 625±20 My.

F. FAULTS

Numerous north-south to north-northwesterly faults traverse the gneisses of Namaqualand. On the map of the eastern part of the area the faults can be followed for great distances along their strikes and there are even more than could be shown on the map. In the western part of the area these faults are not so apparent because of lack of exposure, but they are just as common there as in the east. Hardly an outcrop is examined which does not show some signs of north-south fracturing. In the east, on the edge of the Bushmanland Plateau, the fault lines are marked by kaolinised rocks which appear to have formed along old drainage courses following the lines of fracturing, while kaolinised rocks also occur along faults in several localities where the hills of the Kamiesberg are transected. The faults are usually associated with zones of closely-spaced parallel joints along which the rocks have been discoloured to a reddish hue, complicating recognition of the different types of gneisses. The faults hardly ever appear in the field as a single fracture or breccia zone, and the displacement could only in rare instances be determined. The direction of displacement was determined along some of the faults by the drag of the foliation along their margins, but opposite displacement along some of the associated joints complicated the situation. Very many instances of chlorite-filled fractures were recorded during the survey and the largest fractures are marked by the presence of breccias and of manganese and iron ores.

In a number of localities large pods of sericite have been found along the larger north-south faults. These altered rocks vary in character depending on the rocks traversed. They are usually soft, greenish in colour, dense, and in places earthy; in thin section they are seen to consist mainly of finely divided sericite containing small relics of quartz and felspar. Muscovite appears in some of the thin sections and the rocks also contain some ore, usually in the form of leucoxene, as well as the occasional crystal of zircon.

Some of these rocks contain a fair proportion of kaolinite and the kaolinitic rocks mentioned above are similar in composition, except that they contain a greater proportion of kaolinite; some of the rocks are devoid of sericite. A rock collected to the east of Garies was found to contain more muscovite and the orientation of the flakes produces an indistinct banding. This rock also contains small lenticular aggregates of chlorite and numerous crushed grains of magnetite strung out along the banding. In another specimen calcite also appears as well as some altered biotite, while the quartz is present in unstrained recrystallised aggregates. In rocks which have not been as highly sericitised, thin crush zones, seen in handspecimen as fine anastomising lines of dark ferruginous material, show well-developed mortar structure and dusty ferruginous pellets along lines of movement. The felspar grains are rimmed by sericite which also replaces the mineral in patches. In one of the more kaolinitic rocks opal appears along tiny fractures traversing the rock. The cataclastic quartzose rock from Langedam (3018CD) mentioned before, is seen under the microscope as consisting of lenticular aggregates of highly strained quartz separated by bands of sericite curving around the quartzose lenticles.

Breccias are commonly found along the faults and are usually seen in and along valleys marking the position of fracturing. At Chabiesies (2917AB), however, a silicified breccia forms an almost wall-like outcrop. One of the breccias encountered was found to display rude foliation parallel to the strike of the fault and consists of a dark green matrix containing fragments of pink felspar. In thin section it is seen to contain densely altered and fractured grains of potash felspar and lenticles of strained quartz in a streaky matrix of chlorite with a little epidote. Typically the breccias do not display directional orientation of minerals and usually consist of angular grains of quartz and felspar in a fine matrix of quartz and chlorite, occasionally with some calcite.

In all of the few cases where the vertical displacement along the faults could be determined, the downthrow was found to be to the west, but it is clear from the troughs along which the Nama sediments have been preserved, that downthrow to the east was most prevalent in the south-eastern regions of the area. This also indicates that the blocks between the many faults in the eastern part of the area were largely let down towards the east.

The amount of vertical displacement could only be determined where the Nama sediments were faulted. The largest displacement, at least 200 metres, is indicated by the difference in elevation between the remnant of Nama sediments on Tafelkop (3018CC) and those to the west of the main road. This fault is probably the northerly extension of the fault now seen as a giant quartz vein between Wolwegat and Bitterfontein farther south and termed the Niewoudts Nauwte fault by Brink (1950, p.207). A large vertical displacement also letting down Nama sediments to the west, is seen south of Drie Rivier (2917DC) east of the Buffels River, where the remnants of the sediments have also been tilted to the east on the steps between the faults. This tilting of the Nama sediments is thus opposite to the tilting in the east where the sediments have been inclined to the west.

Quartz veins, usually as long low ridges, mark the line of many of the fractures and they are especially numerous in the southern part of the area. There are so many quartz veins, especially in the south of the area, that they have, except in special cases, been omitted from the maps.

The surfaces of the faults when seen most commonly show striations and these are usually steeply plunging to the north and therefore indicate that the movements were largely vertical, but some with almost horizontal striations were also found. The faults are generally vertical or nearly vertical, but some in the westerly part of the area dip moderately to the west.

The largest faults appear to be those of the north-westerly direction and probably follow lines of structural weakness initiated during the first even (F_4). However, although the geology on either side of these faults cannot always be matched, indicating large displacements, the signs on surface are minimal compared to the surface expression of the north-south faults. The north-south faults have large valleys along their courses in the southern Kamiesberg and there is no difficulty in following the faults across the hills. In the south of the area the faults follow a north-south direction more closely, some trending even slightly east of north, but north of latitude 30°30'S, the faults generally show a tendency to swing to a west of north direction and below the escarpment in the west, the faults again strike mainly due north.

Quartz veining associated with the faults is discussed in great detail by Brink (1950, p.205) who also noticed that the veins occur in reduced numbers to the north. He recorded that repetition of movement along the faults resulted in the crushing of the veins and described them as being high-angle normal faults, usually having a downthrow to the east. The occurrence of a graben structure south of Nuwerus is mentioned so that contrary downthrow is also present. Brink estimated that the vertical displacement along the Groot Riet fault amounted to 3,000 ft., but stated that the magnitude diminishes towards the north.

Transverse faults were found as described by Brink (op. cit., 208-210) and they are not as continuous as mapped by Rogers (1911). Brink believed that this faulting was due to a state of tension prevailing during Dwyka times, but it is abundantly clear from the present survey that these fractures are much older and movement was only repeated along them in post-Dwyka times. Brink ascribed the landward downthrow of the faults in the east to tensional stress attendant on the formation of the Karroo geosyncline farther inland. Rogers (1911, p.14) already indicated that the Kamiesberg lie along the extended axis of the main Cedarberg anticline and that this elevated area may be causally connected with the development of the western part of the folded belt in the Cape. According to du Toit (1939, p.505) and de Villiers (1944), the folding can be dated as Mid-Carboniferous and was renewed during the Permian and later. From the present work it appears that on the contrary the faults have had a very long history of pulsatory movements along them, that the lines of structural weaknesses were initiated in Precambrian times, perhaps even 900 My ago, and that renewed movement along them later displaced rocks of Nama and even Dwyka age.

Pike (1959, p.41) was of the opinion that folding of the Nama sediments was accomplished in its basement along joint planes and fractures seen as breccias, flasergneiss and quartz veins in the gneisses immediately subjacent to the base of the sediments. The presence of epidote and chlorite is recorded in mylonites and breccias below the contact. Jansen (1960, p.64-65) described the post-Nama faults and the formation of horsts and grabens in the sediments and their lateral extension into monoclinal or anticlinal structures. Although he mentioned that the faults do not intersect the granite plutons, the eastern contact of the granite at Rietpoort (3018CC) in the present area is a fault line and the longitudinal outcrops of the granite in the direction of faulting can only indicate that those granites were fractured along the same lines. Similarly, the granites in the western part of the area have certainly been faulted since their emplacement. Jansen (op. cit.) also noted that the syenite complex of Klein Kogel Fontein is located on a fault zone and that the suite of bostonitic dykes was emplaced along faults which were reactivated since the intrusion of the dykes.

To the north of the area Strauss (1941, p.11) recorded that the faults in the O'okiep area trend mostly north-south and except for minor fractures, they all have their downthrow to the east. These faults are all younger than the copper-bearing ore bodies. Vertical displacements of up to 500 ft. are noted there as well as the presence of mylonite and breccias along the lines of the faults. Benedict et al. (1964, p.261-262) had no misgivings about some faulting predating emplacement of the ore bodies and that faulting was renewed at a later stage. North-west and north-east "shear faults" are mentioned (F_5 and F_6?) and while north-south faults are usually breccia faults, "shear faults" of the same strike also occur. They concluded that the fracture pattern suggests north-south compression and that post-noritoid faulting was of minor importance, but that pegmatites were intruded along these dislocations. Since the deposition of the Nama sediments, however, renewed faulting resulted in substantial vertical displacement.

De Villiers and Söhnge (1959, p.31) described the faults across the Rosyntjiebos Mountains in the Richtersveld as step-faulting with the western side moving up relative to the east. East of the Richtersveld the north-west or north-northwest trending faults have been recorded by Gevers et al. (1937), and Rogers (1915, p.73) stated that these faults have been dropped to the north-east along the Neint Nababeep plateau. King (1963, p.238) referred to the east-facing scarp at Steinkopf as being obsequent whereas all the other investigators maintain that the faults in that area have the downthrow to the east.

A similar well-developed fracture pattern is described by Spencer (1959) in the Beartooth Mountains for the Laramian deformation, but is of much greater magnitude than that of the present area. There the horizontal displacement is also small compared with the vertical and the gross aspect of the structure is that of a large asymmetrical anticlinal structure. Step-faulting and graben-and-horst structures are formed and his suggestions as to the origin of the fracture pattern could very well apply to Namaqualand.

From the descriptions and observations of other investigators, it would appear that the majority of faults on the eastern side of Namaqualand have their downthrow to the east whereas on the western side of the present area the regions to the west have been lowered. The high ground forming the Kamiesberg is therefore tectonically controlled and forms an elevated block, largely bounded on both sides by step-faults and as suggested by Rogers, this horst is possibly the northern extension of the western fold belt in the Cape, though it should be noted that its present aspect is largely the result of renewed movement along planes of far greater antiquity.

G. THE FINAL PHASE OF DEFORMATION

East-west fractures, very often marked by the presence of dolerites intruded along them, transect the gneisses and although they are seen in all parts of the area, they are not common. De Villiers and Söhnge (1959, p.115-116) described the north-south faults in the Richtersveld area, but they also reported on cross-fractures striking east-southeast. Strong jointing in an east-west direction is prominent in almost all the outcrops of the Stinkfontein Formation and across these sediments in the same direction are also breccia faults which do not appear to have caused large lateral or vertical displacements. Folds parallel to the joints and faults have not been recognised in these sediments, but in the rocks of their basement minor foliation crenulations have been noticed in the schistose rocks at Oograbies (2917AA). The effects of this deformation were also observed in a thin section of a phyllonite collected north of Komaggas where a fine cleavage developed across the phyllonitic foliation and resulted in the bending of flakes of mica. The quartz lenticles also show columnar straining in the direction of the secondary foliation, but this feature may possibly have been inherited from the earlier deformation.

Displacement in an east-west direction is seen in Plate XXIX, also illustrating deformation during an earlier phase of deformation. Mild curvature with associated jointing is often seen in the incompetent phyllonites and has been observed in thin section as reflected in the mild folding of the foliation.

The Stinkfontein Formation disappears into the sea just south of the mouth of the Buffels River only to reappear on the coast farther south and again west of Bitterfontein (Kröner, 1968). The repeated appearance of the Stinkfontein rocks, striking obliquely to the line of the coast, is undoubtedly largely due to the main phase of folding in those sediments also giving rise to the gently undulating line of contact with the basement, but it is possible that mild east-west folds contributed at least to the reappearance of these rocks to the south.

The east-west dolerite crossing the hills just south of Aardvark (2917AD) beacon is mildly curved, but generally strikes slightly to the south of east. The dolerite could be followed for a distance of at least seven kilometres along its strike, but the fracture along which it has been emplaced was seen another five kilometres farther west. The dolerite south of Soutfonteinkop (3018CC) was followed at intervals over a distance of six kilometres and strikes slightly north of east while the dykes around Groothoek (3018CC) either strike north of east or due east-west. Displacement along the fractures could rarely be measured; the lateral displacement of the large dyke to the north-west of Konde-fonteins Berg trigonometrical beacon is relatively small, being not more than 10 m.

The dykes are correlated with those of Karroo age dated at 190-150 My (Haughton, 1970) and it is only to be expected, as they traverse the Nama sediments, that these rocks were also affected by this deformation. Kröner (1968) recorded the presence of joints in a north-east direction as well as minor folds causing deviations from the subhorizontal orientation of older folds and these could possibly be correlated with this mild deformation.

VI. CONCLUSIONS

1. The gneisses of Namaqualand represent a series of metasediments, quartzites, felspathic sandstones, arkoses, pelites, semipelites and limestones as well as metavolcanics tentatively correlated with the rocks of Kheis age which accumulated on a floor of granitic rocks. The indications are that these rocks are older than 2,600 My as they were intruded by granite at that time. A fairly simple general sequence of metasedimentary rocks has been determined and was found to be consistent over most of the area but, mainly due to subsequent deformation, inverted successions are found and in many places the sequence is incomplete. The simplified sequence as determined is as follows:-

(Top) 6. Mafic rocks and fine-grained biotite gneisses
5. Metaquartzites; minor crystalline limestones in the east
4. Aluminous schists and gneisses
3. Thin but persistent leptites
2. Pink gneisses, absent in the west
(Base) 1. Augen gneisses

If the quartzites are to be correlated with the Kaaien quartzites, then it would appear that the great thickness of Marydale lavas underlying the Kaaien quartzites farther north and to the east, did not accumulate in Namaqualand. It seems possible, however, that the quartzites and associated pelitic rocks here represent the base of the Kheis sequence and do not constitute the southwestern extension of the Kaaien quartzites.

2. The first event of deformation of the Namaqualand gneisses can be compared with the deformation of rocks in similar Precambrian terrains elsewhere and consists of four episodes of folding.

(a) Transposition during the first event is responsible for the tectonic banding in the gneisses and produced a marked foliation surface which provides a plane of reference for subsequent deformation. The first episode (F_1) is expressed in small-scale folds with thickened hinge zones and tapering limbs and is responsible for the destruction of sedimentary structures, discontinuities and gaps in the sequence and the repetition of rock types of similar lithologies. Only rarely could a lineation associated with F_1 be identified with confidence and the indications are that deformation took place under amphibolite grade of metamorphism in the eastern part of the area. F_1 folds were not identified in the west where late deformation contributed to the destruction of earlier folds.

(b) During the second episode of deformation (F_2) the rocks were isoclinally folded and a series of small to very large-scale folds with a strong associated mineral lineation developed. F_2 deformation is largely responsible for the present attitude of the layering in many regions. Although subsequently much deformed it would appear that the axial planes of these folds originally had a dip to the east-northeast and that their hinge lines plunged at moderate to gentle angles northwards. Some mafic bodies were emplaced and mafic sheets were intruded along the axial planes of the folds and in the east, the rocks underwent profound recrystallisation due to high-grade metamorphism. Metamorphic zoning in a north-northwest direction and approximately parallel to the trend of F_2 folds is evident in the mineral assemblages found in the pelitic and mafic rocks with an increasing grade from west to east. At the coast the pelitic rocks consist of muscovite-quartz schists which are found to contain biotite farther to the east where staurolite and garnet also eventually appear in the assemblage. The first indication of another zone of metamorphism is seen in the presence of kyanite and this mineral is found in the pelitic rocks up to the escarpment where its place is taken by sillimanite. This position is also marked in the field by the copious formation of garnet along a zone some five kilometres wide beyond which cordierite appears with sillimanite. Orthopyroxene first appears in the mafic assemblages, but never together with clinopyroxene and these minerals only appear in the same assemblage in the area where granulite-facies assemblages are encountered still farther to the east. Garnet granulites appear south of Springbok, possibly indicating an even higher degree of metamorphism there. The deformation during the second episode took place before the intrusion of the Vioolsdrif granite dated at ±1850 My. Isoclinal folds, seemingly of the same generation as F_2 deformation in Namaqualand, have been described over a wide region to the north and east of the present area.

(c) Large and small-scale east-west folds, responsible for the strike in the banding of the gneisses over much of the area, followed on the second episode and the superposition of this phase of deformation accomplished the formation of basin-and-dome structures on all scales. F_3 folds are variable in style, but are most commonly in the nature of monoclines with the short steep limb, where strong vertical refoliation has taken place, to the south. The strong refoliation along east-west belts resulted in vertical shear zones and movement along tectonic slides parallel or slightly oblique to the layering gave rise to the formation of belts of schistose rocks marked by the presence of sillimanite in the leucocratic rocks and of biotite in the mafic rocks. Along the shear zones marginal folds plunging gently to the east developed, but in the strongly refoliated zones, the folds are tight and steeply plunging. The lineation associated with the shearing becomes more distinct on approaching the zone and is strong in the refoliated zone. The westward trend of the F_3 folds gradually changes to more southwards as the coast is approached, a feature which is ascribed to later left-lateral movement along the coast. Numerous segregation pegmatites and quartz veins were emplaced along the shear zones and incipient formation of granite appears in the axial planes of F_3 folds. Folds of the F_3 generation are present over the whole of the present area and are most strongly developed in the central regions. Shearing in an east-west direction is described for an area farther north and cross-folding in an east-west direction is evident on the maps of the Keimoes area. In the Richtersveld these folds have not been seen, but their presence may be obscured by late deformation there while west of Prieska, east-west trending folds are absent. It would appear that deformation during the F_3 episode was most strong along an east-northeast belt stretching from south of Springbok to Keimoes and that its effects decrease in intensity both to the north and to the south of this zone.

(d) North-west plunging broad open flexural folds, which have had little regional effect on the attitude of the layering brought about by earlier phases of deformation, deform all the folds described above. Refoliation is restricted to narrow axial zones where the main lineations associated with this episode of deformation are encountered. Small-scale folds of F_4 are ubiquitous and are defined by mild undulations in the banding. The folds are not continuous for long distances along their strike and their axial planes, which are vertical or nearly vertical, are marked by strong fracturing and jointing in the larger structures; mild brachy-structures have been formed by the superposition of F_4 folds on folds of the earlier generation. The fourth episode of deformation was also contemporaneous with the emplacement of much granite mainly as phacoliths and concordant sheets which appear to have been intruded from levels below the present exposed surface, but in many cases also from the recrystallisation and local mobilisation of the sediments of suitable composition. The metamorphism of the paragneisses during the fourth cycle can largely be ascribed to the thermal event of granite emplacement when large porphyroblasts of cordierite formed in the pelitic rocks and wollastonite was generated in the quartzite-limestone association. At the same time sphene recrystallised.

The period of granitic intrusion culminated in the emplacement of pegmatites mainly along lines of structural weakness formed during F_4 deformation. The pegmatites usually strike north-west, but are most prevalent along a gently curved east-west belt and, although this belt only appears in the north-western part of the present area, it can be followed across Bushmanland to the east. The pegmatite belt appears to separate the Namaqualand gneisses in the south from the less recrystallised rocks to the north and to constitute the outer and northern limit of a large thermal dome. To the north-east of the belt of pegmatites and north-east of

Prieska, ages of ±2,600 My have been obtained while all the rocks within the belt and to its south have returned ages of 1000 My. This younger date is accepted as the age for M_4 metamorphism.

3. During the second event major shear belts deformed the gneisses of Namaqualand and the resultant structures are consistent with those described associated with shear zones in similar rocks elsewhere. Three directions along which movement took place are recognised and these are in order of decreasing age and intensity: firstly, shearing in a west-northwesterly direction seen all over the area, but most intense along a belt across Garies; secondly, north-easterly shear zones, in places parallel to F_3 zones of deformation; and thirdly, north-south shearing. Along these belts which vary much in magnitude, the rocks have been strongly refoliated and a strong down-dip lineation formed. Marginal folds developed plunging gently, generally westwards in the case of the first direction and generally northwards in the others, but are more tightly appressed and steeply inclined within the confines of the belt of strong refoliation. Fractures follow the same directions as shear zones which also have segregation pegmatites and quartz veins emplaced along them. Mafic dykes have been intruded along north-east shear zones in the westerly part of the area. The mineral assemblages found along these shear belts in the east indicate lower amphibolite-facies metamorphism. By inference it is suggested that north-south shearing took place some 900 My ago and that the "steep structures" of the O'okiep area are largely to be referred to deformation during this event.

4. The lower part of the Stinkfontein Formation, consisting of orthoquartzites with basal boulder conglomerates in places, was deposited along a north-south trough which developed during the second event of deformation. The upper felspathic quartzites, arkoses and interbedded volcanic rocks accumulated during a subsequent phase of deformation when north-northeast troughs developed obliquely across the older sedimentary basins, so that the upper part of the formation overlaps across the basal members onto the basement in places. The main deformation of the Stinkfontein Formation is largely due to vertical tectonics in the floor of the troughs causing gravitational gliding of the sediments from newly-developed horsts into the grabens and continuation of movements resulted in the highly sheared aspect of the rocks along certain zones.

5. During the third event large shear zones, generally showing left-lateral displacement and striking in a north-northeasterly direction, developed in the coastal areas, and although the effects of this phase can be seen throughout the area, they only become significant at and west of the escarpment. Along the

shear zones the rocks were reduced to phyllonites of which the mineral assemblages are those of the greenschist facies of metamorphism. The layering of the gneisses and earlier folds trends are dragged into parallelism and folded parallel to the direction of strike of the major shear zones. A less well-developed set of folds and minor shear zones trending to the north-northwest result in the formation of conjugate folds during this event. Crenulations of the foliation due to movement along subhorizontal planes are seen as shear kink-bands in some places along the major shear zones, but these planes have also been curved by recurrence of slip along vertical planes paralleling the strike of the shear belts.

Many mafic dykes were intruded along fractures developed during this time in the area now forming the coastal plains. These dykes strike north-northeast, north-northwest or north, they have been sheared since their emplacement and they provided the source of the volcanic rocks found in the Stinkfontein succession. Subsequently the Richtersveld granites were intruded with concomitant generation in the schists of biotite flakes and staurolite metacrysts lying across the foliation as well as development of garnet in some of the dykes. Perhaps the occurrence of banded rocks showing disharmonic folding effected when the rocks were possibly somewhat plastic, could also be related to the time when the granites were emplaced. A major dyke, similar in strike and composition to many of the dykes of the coastal area, has been dated as 878±41 My while an age of about 850 My has been determined for the Richtersveld granite. These are then the indications of the approximate age of the third event of deformation and are in concordance with the ages as witnessed by the few determinations of the earlier events.

6. After the deposition of the Nama sediments (±600 My) mild folds deforming the phyllonites developed during the third event and the north-northeasterly folds in the Stinkfontein Formation resulted from the repetition of movement in a north-south direction. Subsequently east-west fracturing took place and along these faults dolerites, transecting also the rocks of Nama age and probably of Karroo age (190-150 My), were emplaced.

7. The movement along north-south lines of structural weakness was repeated and all the rocks were severely jointed and fractured in that direction. Numerous chlorite-filled fractures and cataclastic rocks developed while the graben were formed along which remnants of Nama sediments are seen as tapering fingers reaching into the south of the area. In the east step-faulting with downward movement mainly to the east occurred while step-faulting to the west of the Kamiesberg let the rocks down to the west. The highlands of the Kamiesberg are therefore almost a large horst-like structure possibly forming the northern extension of the western part of the folded belt of the Cape as suggested by Rogers.

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