THE GEOLOGY OF THE OTJOSONDU MANGANESE AREA

SOUTH WEST AFRICA

By

Harold Roper

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THE GEOLOGY OF THE OTJOSONDU MANGANESE AREA.

SOUTH WEST AFRICA

by

Harold Roper

Submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in the Faculty of Science, University of the Witwatersrand, Johannesburg.

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Thesis

ABSTRACT.

Geological mapping and compilation of data from mining and prospecting operations in the Otjosondu area in South West Africa provided the information presented in this thesis. The geomorphology of the area is described and the general geology is discussed. Details of the complicated folding suffered by the Damara rocks are presented. The petrology and petrography of the outcropping representatives of the ancient sedimentary and intrusive rocks is described under the section on economic geology, interpretations of the complex structures of the ore bodies are presented. The mineralogy of the ores was studied by means of polished sections, X-ray diffraction and differential thermal analysis techniques. It is concluded from both field and laboratory evidence that these ores represent the metamorphosed equivalents of syngenetic manganese bearing sediments.

ACKNOWLEDGEMENTS.

The work was carried out under the supervision of Dr.T.W.Gevers, Professor of Geology at the University of the Witwatersrand, and thanks are expressed for his interest and guidance.

Mapping of the area was undertaken for the South West African Administration whilst the author was employed by the South African Geological Survey, and members of the Geological Survey staff including Dr. H.M. Martin, G.K. Joubert and D. Groeneveld are thanked for their interest and comments on the work. Mr. D.J. Malan, Chief Geologist of the Johannesburg Consolidated Investment Company made arrangements for the second visit to the mine and read the manuscript of the thesis.

Thanks are due to the Director of the Geological Survey, the Inspector of Mines, South West Africa, the South African Minerals Corporation and the Johannesburg Consolidated Investment Company for their kind permission to publish this work.

Finally I wish to thank my parents and family for their moral and active support, without which the presentation of the thesis would not have been possible.

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C O N T E N T S.

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CHAPTER I.

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1. Scope of the Work.

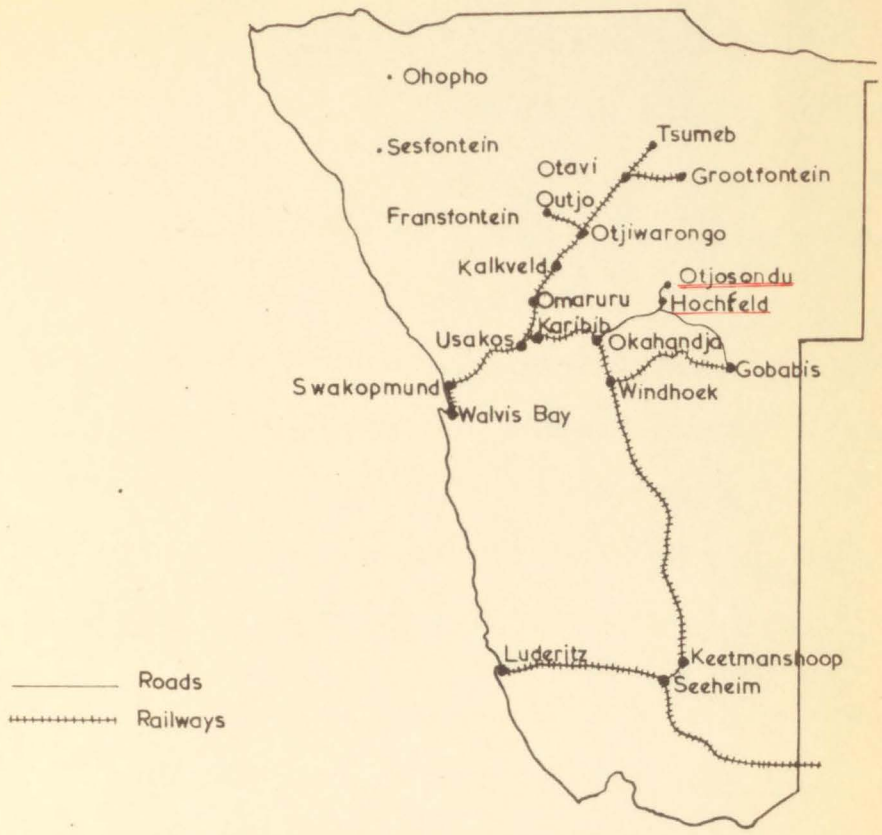
The geology of an area of about 350 square miles on the border of the Otjiwarongo and Okahandja Districts, South West Africa, is described. The description deals with the stratigraphy, tectonics, petrography and petrology of the area together with a more detailed section on the economic geology of the manganese deposits. Conclusions are reached concerning the geological history of the area, and it is considered that the better understanding of this may be the basis of further investigation of both scientific and economic importance.

2. Situation.

The area, which lies at the intersection of the north-east boundary of the Okahandja District, the north-west boundary of the Gobabis District and the south-east boundary of the Otjiwarongo District, consists of twenty farms. Omantumba 134, Okonjete 127 and Etemba Nord 126 lie within the magisterial district of Okahandja, while Eendrag 374, Ebenezer 377, Otjosondu 274, Labusrus 425, Kalidona 277, Weltevrede 396, Ongorussengo 279, Brakwater 397, Oparakane 275, Houmoed 376, Eureka 375, Okaratuo 394, Bosrand 395, Uitkomst 398, Eindelik 399, Omgombeihongora 276 and Ongorussengo Ost 400 are situated in Otjiwarongo. A portion of the southern farm boundary of Ongorussengo Ost forms the northern magisterial boundary of Gobabis.

The meridians 17°43' E and 18°17' E and the parallels 21°5' S and 21°22' S may be considered to bound the area;

FIG. I.



SITUATION OF OTJOSONDU MANGANESE AREA WITH RESPECT TO TOWNS AND TRANSPORT FACILITIES.

the accompanying locality map (Fig.I) shows its relation to the chief towns, rail and harbour facilities.

3. Communications.

The Otjosondu mining area is situated 100 miles from Okahandja, which is the nearest railhead. The mine is connected with this town by an unmetalled road, which is nevertheless open to heavy trucks used in the transportation of manganese ores even during the rainy season. From Okahandja the manganese ores are transported some 200 miles by rail to the export harbour at Walvis Bay.

Roads to the north connect the mine with Otjiwarongo and to the south with Hochfels and Gobabis. In addition, the mining company has constructed an airfield capable of handling light transport planes.

4. Population.

Most members of the farming community in this area are descendants of German colonists who arrived in the area in 1904. The chief agricultural occupation is cattle ranching, and in order that the comparatively sparse vegetation may be used to best advantage in supporting the maximum number of animals, farms are usually divided into several large paddocks and rotational grazing is practised.

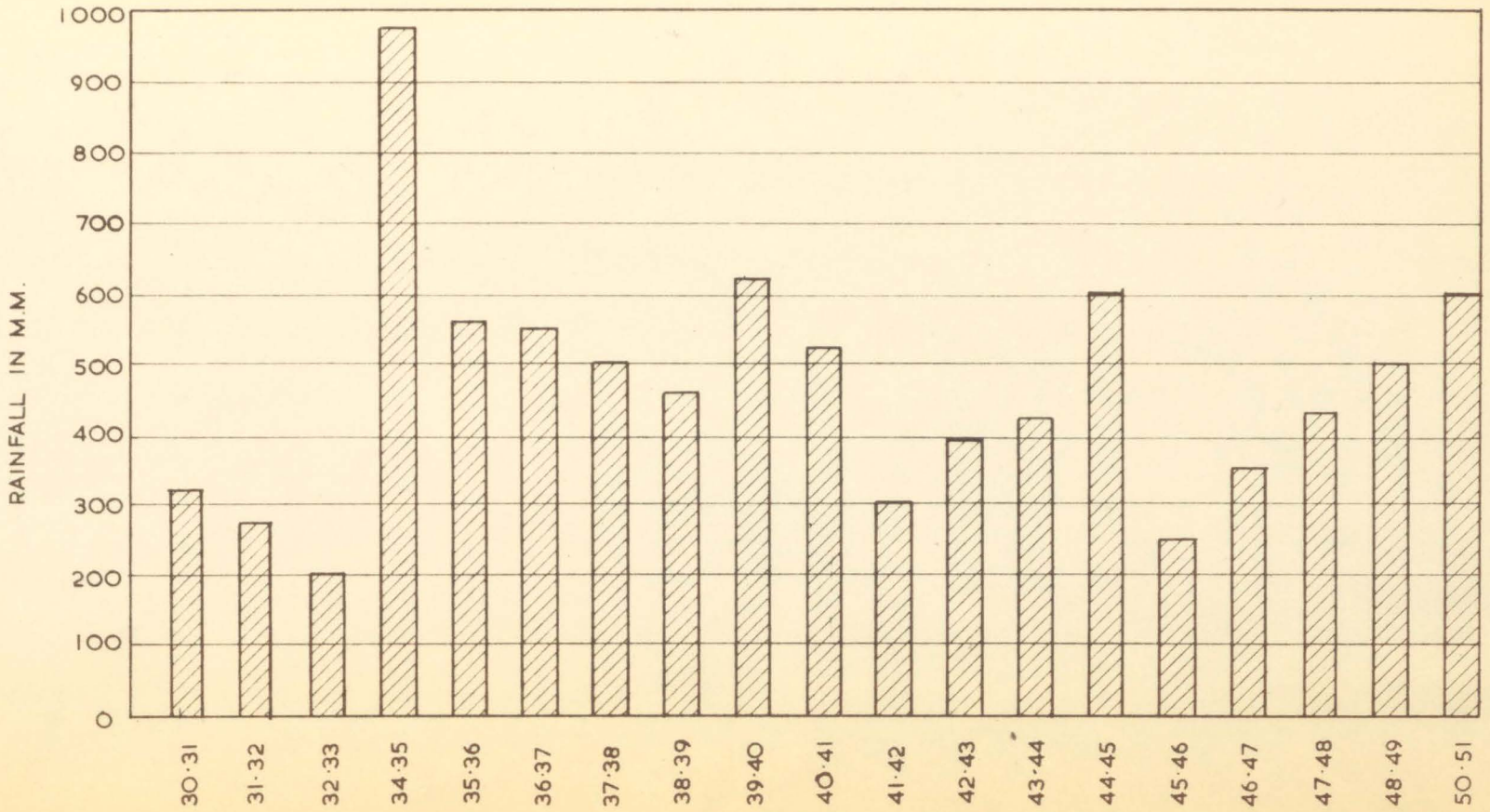
The technical personnel on the mine is in general drawn from the Union of South Africa.

At the commencement of the mining venture the farmers were hostile towards the new industry, but this is no longer the case, for improved transport facilities and better communications are benefiting both groups.

5. Climate and Rainfall.

The average daily temperature in summer is about 36°C (97°F), but temperatures of 42°C (108°F) have been recorded

FIG. 2



TOTAL ANNUAL RAINFALL FOR PERIOD 1930 - 1951.

(FIGURES FOR KALIDONA).

on numerous occasions. During the winter the average maximum temperature during the day is about 18°C (64°F), but during the night temperatures usually drop to about 700C (44°F). Frost has been reported only three times on Kalidona during the period 1930 to 1950.

On an average 18 inches of rainfall can be expected during the year; it is seasonal, months of greatest precipitation being December, January, February and March. Average rainfall figures are presented graphically in Figures 2 and 3.

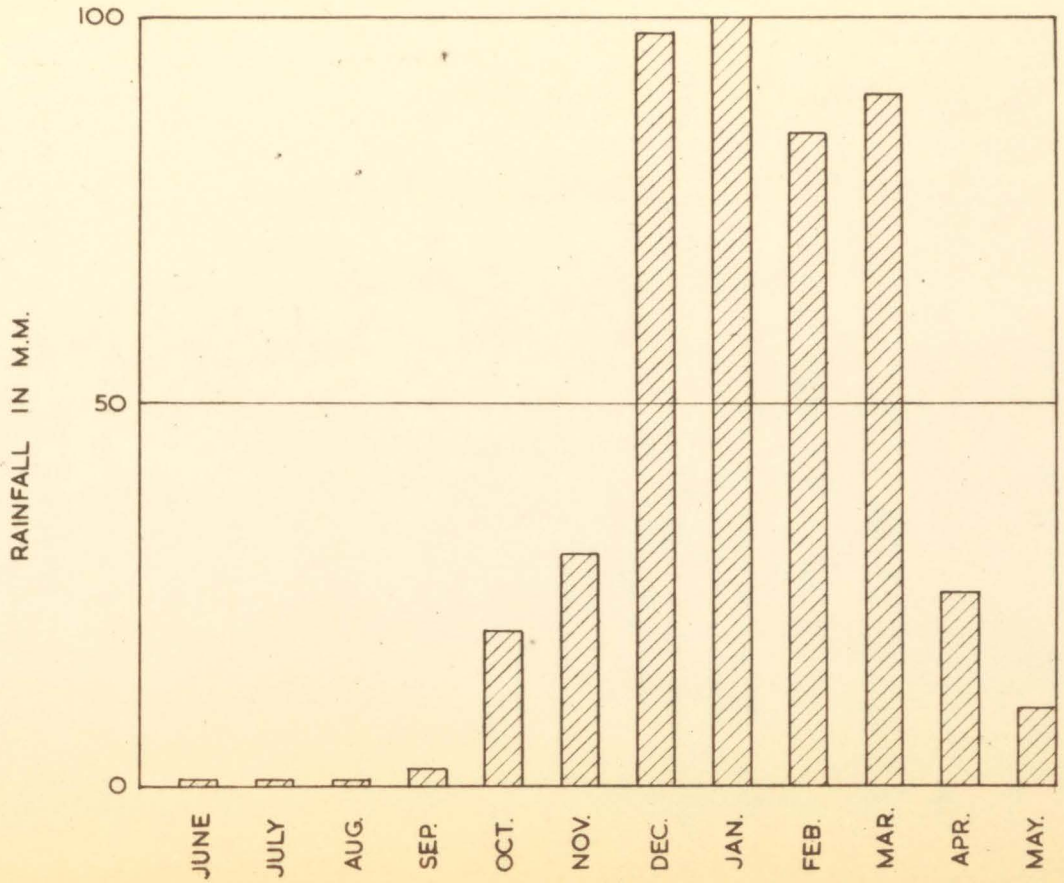
6. Water Resources.

On account of the widespread cover of highly porous Kalahari sand, no surface runoff of water takes place in the area, and the population thus depends solely on ground water for its supplies. As pointed out, average annual rainfall, calculated over twenty years from values recorded on the farm Kalidona, is 18 inches (455 mm), but reference to Fig. 2 will make it clear that precipitation is erratic and that very considerable deviations from the "norm" occur.

As surface gradients are extremely low, practically none of the rainfall is lost to other areas by stream flow, and since, moreover, most of the rocks underlying the porous sand cover are permeable, good supplies of water are usually available in boreholes. It is claimed that at least four boreholes in the area have yields of over 1,500 gallons per hour. The water table stands at an average level of about 100-120 feet (33-40 metres) below the surface.

Schists generally yield good supplies of water, though at least one dry hole in them is reported from Labusrus. The quartzites, due to their sheared nature, which permits easy flow, are also good aquifers. In all

FIG. 3.



AVERAGE ANNUAL RAINFALL DISTRIBUTION.
(FIGURES FOR KALIDONA).

the larger pans, pits have been sunk either by farmers or the mining company, and these have supplied, almost in every case, a certain amount of water. At the present time, however, boreholes are being sited on known faults, and increased yields have been obtained from them.

Some difficulty has been experienced in procuring good supplies of fresh water on the farms Uitkomst 398, Brakwater 397 and Eindelik 399.

7. Vegetation.

The vegetation of the area is dependent on three main factors, viz., the climate, the availability of water, and soil variations.

The climate is suited to the growth of bush and trees able to withstand the winter droughts, and thus the area is one of level bush and tree steppe. The trees are dominantly of the acacia family; "hakiesdoring" or "katnael" (Acacia dentinens), "soetdoring" (Acacia horrida) and "kameeldoring" (Acacia giraffae) being the predominating types. "Ouma" or "kersieblom" (Albizzia anthelmenthica), "witgat" (Boscia albitruaca) and "sukkelbos" (Dichrostachys nutans) are also common. These trees are found chiefly on quartzite outcrops or where quartzite is known to underlie the sand cover at shallow depth.

"Skaapbossie" or " ! Gabbabos" (Catophractus alexandri), "Appelblaar" (lonchocarpus nelsii), "suurkruisbossie" (Grewia flava), and "persblom" or "kurkstruik" (Mundulea suberosa) are also found in the area. Further information with regard to these species can be found in a publication by Boss and Greeff(1937).

The factor of water availability not only affects the type of vegetation but, coupled with the sandy nature of the soil, imposes a barrier to the even distribution of plant growth. When rain falls, part of it rapidly

percolates through the porous sand cover down towards the water table, and although the deep sands retain a certain amount of moisture, the rest is rapidly lost to the atmosphere by evaporation. Where bedrock is fairly deep beneath the sand cover, water in quantity is therefore available to plants for relatively short periods only and in such localities mainly low scrub and grass grow. Where water is available to plants for longer periods and trees can take root, the taller arboreal type of vegetation flourishes. The latter is practically confined, as previously mentioned, to outcrops and near-surface occurrences of the resistant quartzites eroded to a lesser extent than the associated schists. This vegetational feature has been made use of in the compilation of the regional map.

In the eastern section of the area marbles also form outcrops, and here, too, a more luxuriant growth of trees and bush is in evidence; the type of tree, however, is not the same as that growing on the quartzites. In the extreme south-east, where schists rise through the sand towards the surface, calcrete has developed above them, with the result that these outcrops support growth of the same type as the marbles.

Apart from the fact that the depth of sand-cover has an important effect on vegetation, the composition of the underlying rocks exerts further influence on the type of tree and bush rooting on them. The lime-desiring "skaapbossie" is found growing on surface limestones and marbles only. The acacia group and other larger tree types are confined to the quartzites. The "appelblaar", "suurkruisbossie" and "persblom" are apparently able to survive on the deeper sandy soils. Tree growth thickens on or close to ore outcrops. This is due to the fact

that sand cover in general decreases over these horizons and, furthermore, pegmatites which have intruded them enrich the soil in potash and certain trace element nutrients.

8. Previous Geological Work.

Prior to 1949, when the manganese deposit was prospected, no regional survey work was conducted in the area. Mining commenced almost immediately and geologists concentrated their attention on known outcrops of ore. The area was subsequently visited by several consulting technologists in the various fields of mining; however, little systematic work was done. Preliminary geophysical work was undertaken by a consulting company, but it appears to have been of little value. Some regional ground magnetometric traverses, and a few local ones across the ore bodies, together with a gravimetric survey to obtain possible depths to which the ore bodies could be expected to extend, were the sum total of the undertaking. Subsequent to the commencement of this research, much more detailed geophysical work has been undertaken but no information from this is available for inclusion at the present time.

Samples of the ore were submitted to the Geological Survey for identification, and on these a microscopic study of the manganese minerals was carried out by de Villiers (1951). Two short mineralogical papers on the same material were submitted by Vermaas (1952, 1953). These papers deal with the barium felspars and manganese-iron garnets associated with the ores, but no reference to their origin is given.

Joubert and Martin, both of the Geological Survey, visited the area, and a sketch plan was compiled from aerial photographs. This showed up the complexity of the

folding, but, as time was very limited, no detailed work was conducted by the geologists. Certain aspects of the deposits were then described by Joubert (1952).

A few unpublished reports by geologists who visited the mine in a consulting capacity were made available to the author by the mine management, but these were written at the start of the mining venture and are rather generalised. They did, however, guide further research and pointed out certain specific problems of structure and ore deposition, on which no agreement was reached and these are dealt with in the present investigation.

The author (1956) published a brief report on the field, but slight modifications in the stratigraphic sequence have subsequently been made.

9. Objective of Present Investigation.

After mining had commenced at Otjosondu it became increasingly evident that only by a good understanding of the structural geology, which in turn was dependent on a regional survey of the area, could ore-bodies be followed. This fact prompted the visit of Martin and Joubert to the area and, after subsequent discussion, it was decided that the deposit was of sufficient importance to the South West African Administration to warrant a detailed study from the regional and economic aspects; this formed the basis of the present investigation.

The area was mapped by the author during the field-season of 1954. The regional mapping was done directly on aerial photographs in the field, and this was later transferred to base maps. A second visit was made to the area in 1958, and detailed mapping of ore bodies was undertaken. A few modifications were made to the regional map.

As the area is, for the most part, a sand-covered

plain, rock exposures are few and far between. This raised once more the thorny question of the best method of cartographic representation for the regional geological map. A map of actual rock outcrops in the Otjosondu area would show only small isolated quartzite and limestone exposures, and would thus not only be difficult to read but would also grossly underestimate the amount of definite information which has been obtained in the area. All important structural aspects would be absent from such a map.

As has been mentioned, the morphological variation between areas underlain by hard quartzites and softer rock types is striking both on the ground and on aerial photographs. This feature was used in conjunction with all borehole information and other geological indications to fill in the inferred geology.

The regional map appended herewith is shaded in two tones for each rock type, the darker shading representing actual outcrops, and the lighter colour showing the probable underlying rock type.

Detailed structural work was done in part on maps of ore bodies which were available in the mine survey office, as well as on newly drawn ones. A large amount of new data was compiled and, with present concepts of both regional and local surveys, new interpretations have been made.

10. Summary of the Geology.

As is shown in Table I, the oldest known rocks in the area are sediments of the Damara System, which, after deposition were overfolded from the north-north-west; thus most dips are towards the north. Some faulting occurred across the fold axes. During, and soon after, the folding, grey granites were introduced, either by

injection or by in situ granitization of the pelitic sediments (schists).

During the final phases of the tectonic activity the red granites and pegmatites of the Salem period were intruded into the sediments. Then followed a long period of erosion and peneplanation. Subsequently, sediments of the Upper Karroo System were deposited, but these in turn, have been eroded away, except where they were protected in former deep glacial valleys formed during the Lower Karroo Period.

The present level of erosion conforms fairly closely to the peneplained surface upon which the lowest of the Karroo rocks were deposited.

Finally, in Pleistocene to recent times, wind-blown sands (Kalahari) were spread across the region.

TABLE I.

MAIN GEOLOGICAL DIVISIONS.

Igneous Rocks	Formations	Period
	Sands	Kalahari to Recent
	Etjo Sandstones	Upper Karroo System
Red porphyritic granite, red non-porphyritic granite and pegmatites		Salem
Gneiss-granite		Pre-Salem
	Upper Schists Marbles Upper Quartzite Itabiritic Schist with Ore Lower Quartzite Lower Schists and Gneiss	Damara System

CHAPTER II.

GEOMORPHOLOGY.

1. Physiography and Drainage.

The area under discussion lies within the transition from the "Plains of northern Damaraland" and the "Sandveld" (Wagner, 1916). In the western portion of the area the level, sand-covered plain is surmounted by two eminences composed of resistant quartzite, viz., Otjosondu Kop and the Okonjete Hill (Plate I). They are typical "inselberge".



Plate I. A view looking northward over the peneplain from the Otjosondu Kop. The rock in the foreground is quartzite whereas the plain is underlain by marble and schist.

Further east, however, the wide expanse of Kalahari sand is unbroken. This is due no doubt to both the thickening of the sand cover in this direction, and the fact that flatlying Karroo beds are developed in this region. Describing the plains of Northern Damaraland, Wagner states that: "Towards the east the plains merge gradually into the sandveld of the Kalahari". King (1942) describes this transition in the words: "On the east the rock cut plains

are gradually smoothed out by the sands of the Kalahari". To the west of the area, more inselberge protrude through the sand cover, and the landscape is then typical of the plains of Northern Damaraland.

The average elevation of the plain in the vicinity of the mine is about 1,460 metres, and the height of the only trigonometrical survey station in the area, Otjosondu Kop, is 1,579.3 metres. The plain rises southwards and attains a height of about 1,650 metres just south of Hochfels; it is graded northwards to the Omatako Omuramba.

Since the area is very flat, it is one of internal drainage. Although during particularly wet seasons isolated shallow run-off courses, draining northwards, may carry surface water intermittently for brief periods, the latter soon seeps away through the sandy floors. The shallow, grass-covered run-off depressions are known as OMIRIMBA (sing. OMURAMBA). Where silting has destroyed any gradient, the omuramba may form a series of very shallow pans and these as a group develop into vlei-like features known as ERINDI. The beds of these erindi are often formed by a black clayey loam containing lime nodules, or by a solid sheet of surface limestone.

The orientation of the omirimba frequently follow faults which lie across the grain of the country i.e., at high angles to the fold axes; but this is not invariably so.

Pans are a feature in this area, as they are throughout the whole of the Kalahari region (Plate II). They are shallow depressions which vary in diameter from less than 25 feet to several hundred yards, and are generally classified in accordance with the material forming their floors, viz., bedrock pans, limestone pans, loam pans and sand pans. All the above types are observed within the area mapped.

The pan on Okonjete 127 is an example of a bedrock pan, hard white quartzite forming its bed. It does, however show a relationship to the limestone type, as this material is being deposited along its margins.

Limestone pans, which are the most common type in the area, are often very large, the one on Etemba Nord 126 being over one mile in length. Loam pans are developed in the erindi, whereas sand pans chiefly overlie the quartzites.



Plate II. General view of a small sand pan on Ogorussengo 279.

The water of the pans usually present only during the rainy season, is never strongly saline but only slightly brakish or even fresh.

Much has been written about the origin of pans. It would seem that within the Otjosondu area some are related to faults, whereas others are the result of wind erosion. Erosion by animals seems to have played a major part in the development of most of the minor pans, and this process is still continuing, if not by the agency of wild life, then assuredly by farm stock.

2. Erosional History of the Area.

A long period of erosion antedates the Karroo sediments. It is considered probable that the pre-Karroo landsurface was greatly modified by ice action in early Karroo times. Following this cycle, the Upper Karroo (Etjo) beds were deposited on an uneven surface, the Okonjete Hill and Otjosondu Kop projecting as manadnocks into the Karroo sediments. To the east, Karroo sediments appear to be preserved in an infilled glacial valley as elsewhere in Southern Africa. Martin (1953; 1957) has described striking instances from South West Africa, whereas Cousins (1950) has reported similar features in the Odendaalsrus area of the Orange Free State.

The relatively recent removal of the Karroo rocks has laid bare the former surface, and thus the topography is in part referable to the pre-Karroo landscape, and represents a fossil topography of Upper Carboniferous Age.

During the Kalahari period,and even in recent times several periods of pronounced aridity must have occurred as evidenced by silcrete layers observed at several sites throughout the area. This factor is of economic importance since the upper few feet of manganese of some ore bodies have been adversely affected by the addition of silica. It is not possible to correlate these horizons with the occurrence of the basal silcrete layer of the Kalahari system as insufficient data is available.

CHAPTER III.

GEOLOGY.

The geology of the area will be described in chronological order from oldest to youngest rocks. Detailed descriptions of rock types are given under "Petrology", and the geological horizons present in the area are presented in Table II.

1. Rocks of the Damara System.

(a) Lower Schist and Gneiss Zone.

The rocks of the Lower Schist and Gneiss Zone form true outcrops only on Kalidona, but their existence is proved throughout the southern and western areas of the map where they have been intersected in all the water boreholes drilled. Rocks of this type are known to outcrop all along the Hochfels Road, and thus it is probable that this group is folded in a series of anticlinoria from the Okonjete Hill to south of Hochfels.

Since no definite marker horizon exists, and outcrops are very limited, these rocks have not been extensively sub-divided, nor has their thickness been determined with much accuracy. A twofold sub-division may, however, be made between the schists and a thin marble band ($\pm$ 5 metres) which lies immediately below the Lower Quartzite Zone.

The rocks of the whole group vary quite considerably, depending on their bulk composition prior to metamorphism. The predominant type is a quartz-biotite-felspar rock which varies from a schist to a granulite in texture. Where lime is present in the sequence the rocks show variations from a pure graphite marble (south western point of the map) to plagioclase-pyroxene-garnet and scapolite-diopside gneisses.

TABLE II.

STRATIGRAPHY OF THE OTJOSONDU MANGANESE AREA.

System or Age	Series or Period of Igneous activity	Stage or Zone	Character	Maximum Thickness	Igneous Rocks	Type Area
Recent			Sand, alluvium, calcrete	From less than 1 metre to over 10 metres.		Ubiquitous
Kalahari			Red sands, silcrete, ferricrete calcrete	From less than 1 metre to over 10 metres.		Brakwater Kalidona
Upper Karroo		Etjo Sandstones	Sandstones	240 metres		Okamatangara
pre-Karroo	Salem (?)				Acid pegmatites, red porphyritic biotite granite	Ubiquitous
post-Damara	Pre Salem (?)				Grey Biotite Granite	Okonjete etc.
Damara	Marble Series (?) or Khomas Series (?)	Upper Schist	Biotite schists and gneisses	-		Ouparakame
		Marble	Marbles calc-silicate rocks, and gneiss horizon	+ 100 metres -		Weltevrede
		Upper Quartzite	Impure quartzite	+ - 50 metres		Otjosondu
		Itabiritic Schist	Itabiritic schists carrying three manganese ore horizons	+ - 20 metres		Labusrus
		Lower Quartzite	Pure white quartzite	+ - 70 metres		Otjosondu
		Lower Schist	Schists, granulites marble, calc-silicate rocks and gneiss	Probably over 500 metres		Kalidona

(b) Lower Quartzite Zone.

The rocks of this zone are coarse-grained quartzites which form the Otjosondu Kop and the Okonjete Hill, other good outcrops being exposed on Labusrus, Bosrand and Weltevrede. Megascopically the rocks are seen to be made up of very coarse interlocking quartz grains. The unweathered rock is pure white, and individual crystals are clear, attesting their purity; but on weathering they become pinkish or black, due to iron and manganese staining, respectively. Towards the top of the zone a little specularite appears in the quartzites, and towards their base some muscovite is observed in hand specimens.

On account of the purity of these quartzites, their clastic and sedimentary origin was checked by heavy mineral determinations, the results of which are given later.

Almost every trace of bedding has been obliterated by intense metamorphism; instead shear planes have been developed which transsect the quartzite and may be seen on close inspection of hand specimens. Individual quartz grains are oriented in a direction parallel to these planes.

Dip measurements on these rocks are complicated by a distinct set of joints which themselves dip at high angles to the north. These joints are also closely allied to the shear planes observed in hand specimens, and both will be discussed under "Tectonics".

(c) Itabiritic Schist Zone.

The Itabiritic Schist Zone may be sub-divided thus:-

Upper Ore Horizon
Itabiritic Schist
Middle Ore Horizon
Itabiritic Schist
Lower Ore Horizon.

The manganiferous horizons are represented in outcrop by black rocks which are peppered with lighter gangue minerals such as quartz, pink and yellow garnet, felspars introduced by pegmatites and a blue opaline mineral. Sometimes the gangue is present in definite layers, thus emphasizing remnant bedding. The contacts with the quartzites are generally very sharp, whereas those with the schists are less distinct. The ore bodies appear in outcrop to be lenticular but, as mining proceeds, the ore horizons are being found to extend beneath the sand cover.

At Ebenezer South a gradation between manganese ore and the itabirite schists has been noted, the change taking place within a few centimetres. Furthermore, throughout the area, rare lenticular bodies of itabirite are seen to be developed within the manganese horizons, and as the bedding of these lenses is parallel to the local bedding, contemporaneous deposition of the manganese and schist material is indicated.

The thicknesses of the ore bands are rather variable, but individual horizons do not exceed 5 metres, and are generally about 2½ to 3 metres.

The itabirite schists are very useful as a marker horizon, but they weather negatively and never form outcrops. They are, however, observed throughout the area in mine and prospecting workings.

Close to their base, i.e., directly above the Lower Ore Stage, the schists are haematite-rich, and this mineral persists in variable quantity throughout the zone. Where little argillaceous material was present originally, the schist is a regularly banded rock composed of well defined layers of specular haematite and quartz, individual layers ranging from a few millimetres to over 3 centimetres. The specularite plates are oriented parallel

with the banding, and give the rock a marked schistosity. Magnetite does not occur in any of the specimens studied.

The quartz bands vary in colour from white and vitreous to dark steel-grey, and consist of an interlocking aggregate of coarse and fine quartz grains together with small crystals of haematite, which still retain their marked orientation. In some few cases kaolinite was observed with the quartz, suggesting that some felspar was originally present in the light bands.

A complete gradation from haematitic quartzite through itabiritic schist and then to biotite and hornblende schist is observed. The biotite schists owe their schistosity to the parallel orientation of both the specularite and biotite. This rock-type has been prone to alteration by magmatic influences, and locally it has become an augen gneiss, the eyes being formed of felspars.

All these rock types are described under the heading of "Petrography".

(d) Upper Quartzite Zone.

The rocks of this stage are pure quartzites which grade upwards into felspathic quartzites and form outcrops on Otjosondu, Labusrus, and Bosrand.

It is generally difficult to differentiate between quartzites from this horizon and the Lower Quartzite Zone; however, if a fair amount of felspar is observable in the hand specimen, it is probable that it is derived from the Upper Zone. Towards the base of the zone a gradation between quartzite and haematite schist has been noted. This is especially marked at Labusrus Central workings.

(e) Marble Zone.

The rocks of the Marble Zone overlie the Upper Quartzites and are best developed in the eastern portion

of the area, where they form slight rises in contradistinction to the normal negative weathering which they undergo throughout the rest of the area. Due to the lack of outcrops and the fact that the schists and limestones cannot be differentiated easily on aerial photographs when covered by sand, the boundaries of the Upper Schists and the Marble Zones are for the most part tentative.

The Marble Zone is divided into the following horizons:-

Upper Marble Horizon.
Gneiss Horizon.
Lower Marble Horizon.

The pink granite-gneiss is considered to have been formed by granitization of a former pelitic horizon, remnants of which remain in a few isolated outcrops.

Calcareous rock types of this zone vary quite considerably in composition and mineral assemblage. The dominant outcropping representatives are marbles, which vary in texture from fine to coarsely crystalline, and in colour from pure white to grey, grey blue, and pink. They generally carry some crystalline graphite and emit a sulphurous odour when shattered, thereby earning the name "stink-kalk".

Periclase and brucite marbles appear in the assemblage, while diopside and tremolite marbles represent the impure facies of the limestones.

Where the purer marbles have been caused to flow, the rhombs of calcite have been distorted and, in hand specimens, they assume lens shapes.

(f) Upper Schist Zone.

Rocks of this stage do not outcrop, but their existence is known from boreholes and pannings of slimes. They overlie the rocks of the Marble Zone and occur

chiefly in the north-east of the area.

In a well on Okaratuo highly altered specimens of these biotite-quartz-felspar schists were found in secondary limestones, and elsewhere the presence of rubble and mica flakes in the surface limestone around pans indicates the underlying rock type.

2. The Granites and Pegmatites.

The granitic rocks of the area are conveniently divided into five groups:

(a) Gneiss-granite.

These rocks, which have an undoubtedly mixed origin occur within the Upper and Lower Schists of the area. Contacts between them and the schists are ill-defined, for they generally resemble the latter rock type both in their microscopic appearance and their mineralogical composition. They are as a rule grey in colour and are considered to be the equivalent of the Gneiss-Granites described by Gevers (1929) from North-Western Damaraland.

(b) Red Porphyritic Granite of the Bosrand Area.

This granite occurs as a concordant intrusion within the Upper Schists. In the hand specimen it is a coarsely porphyritic biotite granite with a striking red colour. It is considered to be the equivalent of the red granite described by Gevers (1929) from North-Western Damaraland. He considers that it represents a phase midway between the Salem granite and non-porphyritic granites. In (1934) the same author described a red porphyritic biotite-granite from the Windhoek area. It is noted that it differs from the typical Salem granite by the unusually red colour of its felspars and the common occurrence of epidote. de Kock (1934) named it the Kobus granite but it appears that all three occurrences represent the same rock type.

(c) Red Non-porphyritic Granite.

Within the Marble Zone of the area red non-porphyritic granites which often show graphic intergrowths of quartz and felspar are noted. These are generally concordant with the structural trends, however, in areas where the Lower Marble Horizon is absent this rock is found to grade into the Upper Quartzites of the area. The red non-porphyritic granite appears to be absent to the north of the Otjosondu Kop.

The origin and correlation of this granite is problematical. The rock generally does not carry femic minerals, and has been noted to pass laterally into rocks which have a sedimentary origin, crystallized arkoses and quartzites. It was concluded that it had a metasomatic origin, however it appeared to be unusual in that the marbles show little change in mineralogy as these granites are approached. It appears however that a definite horizon within the marbles must have been altered, and this feature has been noted elsewhere in literature. Minch (1949), confronted by a similar problem stated that "Whereas slate is undoubtedly less pervious to aqueous solutions than limestone, their metamorphic equivalents must be supposed to act differently under conditions of granitization. Now metamorphic argillite would be more pervious, consisting of a granular fabric of silicate minerals (and being in case of synkinomatic granitization in a state of active differential movement); and, having an excess of aluminium, metamorphic argillite would have a strong tendency to precipitate alkali from permeating solutions rich in alkali. On the other hand, under the existing high pressure preventing escape of its CO_2, marble would be less pervious to these solutions; at the same time, it would have no tendency of precipitating

alkali from solutions rich in it. Also, under pressure marble might plastically flow and hence be less permeable than schists traversed by active shearing planes".

It is considered that the granitization processes took place during the Salem period of granite intrusion.

(d) Pegmatites.

These rocks are as a rule concordantly intruded within the itabiritic schist horizons, but discordant veins cut the ore horizons. The rock is striking in the hand specimen, being corasely crystalline. Glassy quartz occurs as large, irregular particles within the rock, and although the felspars are generally pink and red, grey colours are noted.

(e) Granitic gneisses associated with pegmatites.

The itabirite schists often show the development of augen structure where cut by the pegmatites, and in certain areas the itabirite horizon has been almost completely altered to a haematite bearing granite gneiss. This demonstrates the ease with which granitic species of rocks were able to form in situ by pneumatolytic action on the older sediments.

Details of the mineralogical changes associated with the granitization phenomena observed in these rocks will be given in the chapters dealing with petrology and petrography.

3. Rocks of the Karroo System.

After the intrusion of the pegmatites the whole area suffered a long period of erosion, alternating possibly with deposition, the sum total of which was to lower the surface of these ancient rocks right up to the time of deposition of the Karroo sediments. Prior to the deposition of the Karroo beds, the whole area suffered

extensive erosion, the pre-Karroo landsurface being subsequently modified by ice action.

The survey failed to detect any Karroo rocks in situ within the area, but on the farm Okamatangara, just to the north of the area mapped, some 740 feet of sandstone was passed through in a borehole which was drilled to this depth in the hope of finding oil. It was subsequently used for water supply. These rocks were examined by T.W. Gevers at the time of drilling, and he considered them to be Etjo Sandstones.

It would appear that only the Etjo (Stormberg) Series of Karroo rocks was deposited in the area. Along the north-west side of the Etjo Mountain the Karroo beds have been downfaulted against granite; and it was considered that the Etjo sandstones of the area under discussion were preserved in a similar way by a fault with a considerable downthrow to the east. From geophysical evidence, however, it appears that they must occur within a former glacial valley, such as those described by Martin from elsewhere in South West Africa.

A few pieces of rubble, which may well be material of Karroo age, have been found on the Upper Schists, and together with these some rounded basalt pebbles were noted.

4. Kalahari Period.

Some of the sand in the eastern portion of the area is undoubtedly of Kalahari Age. The sand here deepens considerably, with the noticeable effect that tree and bush cover decreases. In contrast with the sands of the western area, these sands are usually more reddish in colour.

Ferricrete and silcrete of probable Kalahari age are developed near the large pan on Okonjete and at the former workings to the east of the present Otjosondu East

workings. They are, unfortunately, not well exposed, and little more can be said of them. Also connected with this period is the slight silicification of the top few feet of the ore throughout the area.

5. Recent Period.

Recent sands and calcretes are abundant throughout the area. The calcretes tend to form almost ubiquitously where water collects and evaporates. They cover extensive areas to the south of the Okonjete Hill and overlie schists, marbles and pegmatites in the east of the area. Pan limestones are often fossiliferous.

The Recent sands can only be differentiated from the Kalahari sands on the basis of colour, for the latter are generally reddish, whereas the former are white.

CHAPTER IV.

GEOLOGICAL HISTORY OF THE DAMARA PERIOD.

1. Deposition of the Sediments.

The Damara System as exposed in this area consists of metamorphosed argillaceous, arenaceous, calcareous, manganiferous and ferruginous rock types. The quartzites are derived from former quartzose sandstones or orthoquartzites, whereas the schists are representatives of former shales and marls. The itabiritic quartzites and schists are derived from ordinary banded ferruginous cherts (banded ironstones). These must have been admixed with fine argillaceous material, which is present as biotite in the itabirites of some areas. The manganese ores are considered to be the highly metamorphosed equivalents of former psilomelane and pyrolusite beds which were a particular phase of the banded ironstone succession. Marbles are derived from limestones which were in part of biochemical origin, as evidenced by the presence of carbon and hydrogen sulphide in this rock type.

The depositional history of the area can be represented on a cyclothem diagram (Figure 4). The lowest beds were shales, and deposition took place in deep water. Fluctuations in the supply of clastic material and the resulting acceleration of carbonate deposition led to the development of marls within these shales. The supply of clastic material then decreased sharply and a thin limestone was deposited under stagnant conditions, for organic remains accumulated in the sediment, and are now represented by graphite flakes in the marble.

A period followed during which typical shelf deposits accumulated. It was heralded by the deposition of very pure sand which was probably washed and reworked several

DIAGRAMMATIC REPRESENTATION OF DAMARA CYCLOTHEM AS DEVELOPED AT OTJOSONDU.

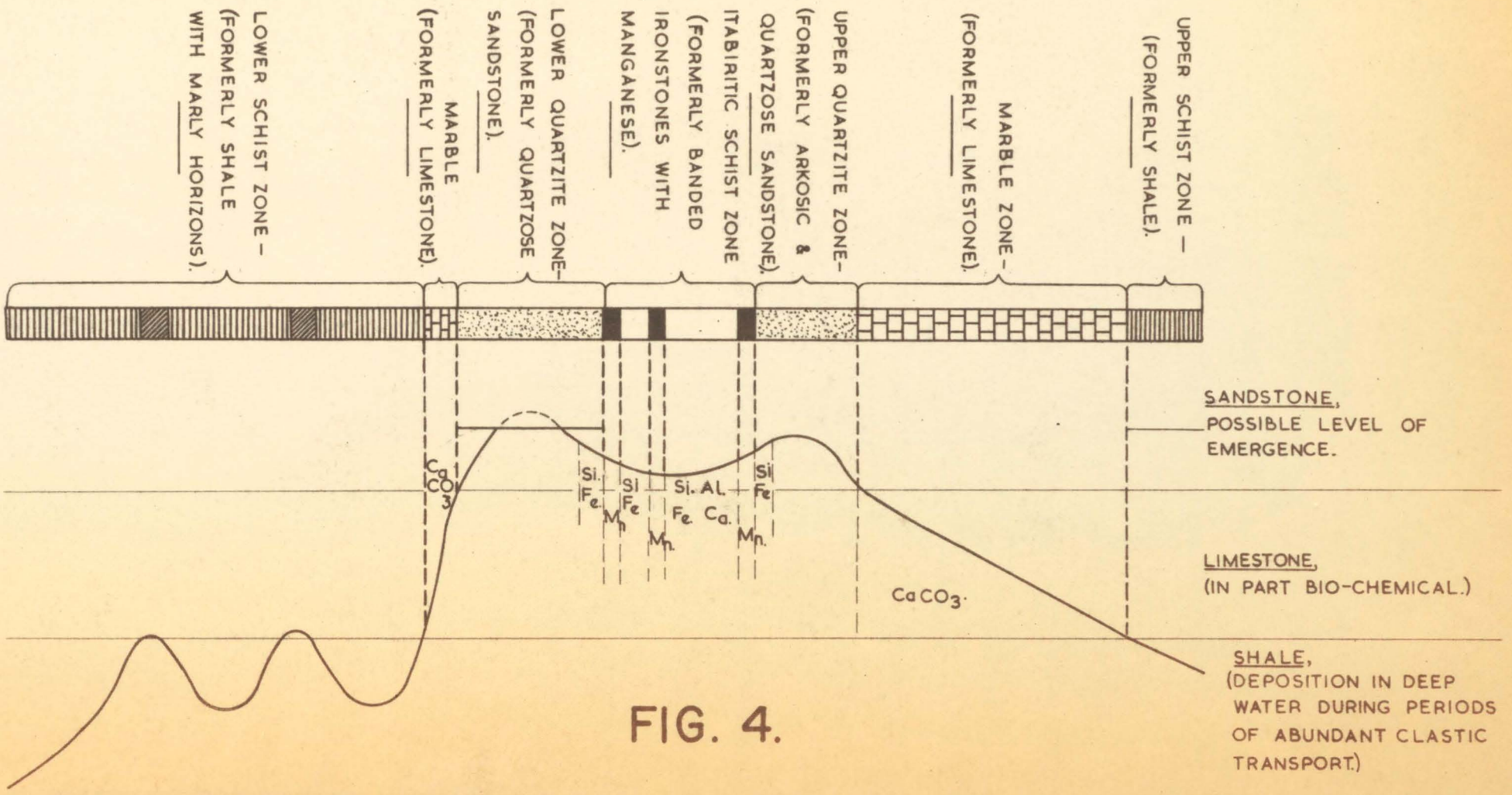


FIG. 4.

times. A return to chemical deposition now took place but, whereas calcium carbonate was formerly the most important precipitate, its place was now taken by iron, silica and manganese. The iron oxide-chert succession is recognised to develop under typically these conditions (de Sitter 1956) and from examples in India (Fermor, 1909), Brazil (Durr, 1944) and now South West Africa, it would seem that manganese is often deposited with the coarse clastic members of the sedimentary series. During this chemical deposition the finer materials from the quartzose members, now being deposited elsewhere at this time, were added to the banded ironstones, and these became somewhat argillaceous. After the deposition of the third manganese-rich horizon, arenaceous detritus was once again deposited. During the deposition of the Upper Quartzites, the supply of material was probably greater, and either the sorting action of water less effective, or climatic change occurred with the result that these rocks now carry felspar towards the top of the succession.

After deposition of the quartzose material ceased, limestones once again were developed, but conditions reverted to the point where the cyclothem began and fine mud accumulated.

The typical cycle as described above occurs throughout the Damara System, with the notable exception that manganese and iron were not always deposited. On the macro scale the whole System is divided into a Lower Arenaceous group, a Middle Marble group and finally an Upper Schist group. This represents a succession in which sediments were deposited in a slowly sinking basin. On the micro scale it has been observed that some schists have calcic-rich layers and argillaceous layers, which led to the formation of different groups of metamorphic minerals in a single hand specimen.

2. Folding of the Sediments.

After deposition, the sediments were folded along axial planes which strike slightly north of east and are overturned to the south. No evidence, such as thickening and coarsening of beds, which could be due to folding during the deposition period, was noted.

The outcrop pattern shows that the rocks were unable to extend laterally by stretching and the result was that movement in a vertical direction resulted. "Crossfold" structures, whose axes lie at right angles to the regional fold axes, and the rapid reversal in direction of the plunge of the major axes all confirm that the vertical movement of the beds was considerable. The movement in the vertical plane resulted in the formation of a regional cleavage which has modified the appearance of the rocks. The tectonic aspects of this will be discussed later.

Faulting is typical of the type associated with strong folding at great depth. At least one significant wrench fault has been noted by geophysical methods, and outside the area other faults of probably the same type are important from the prospecting point of view.

3. The Granite Intrusions.

The first granitization phase did not modify the tectonic pattern of the area in any way. Mineralogical change rather than structural effects are observed, for the growth of felspars and the development of augen-gneisses were brought about by addition of material, not by intrusion but by diffusion phenomena.

The intrusion of the red porphyritic granite and the granite pegmatites also did little to modify the pattern, but their orientation, mode and position of emplacement were all directly governed by the tectonic forces which controlled their intrusion. They were intruded along

planes of easy ingress, where, either due to the nature of the rock type, or significant structural effects, their emplacement was permitted.

4. Correlation of the Quartzites, Schists and Marbles.

The highly folded quartzites, schists and marbles of the area are correlated with the Damara System of South West Africa. The sub-divisions of this system as proposed by Gevers, Frommurze and de Kock are given in Table III.

TABLE III.

SUB-DIVISION OF THE DAMARA SYSTEM.

Western Damaraland (Gevers, Frommurze, 1929).	Windhoek and Rehoboth (Gevers,1934, and de Kock,1934)
Khomas Series (Biotite Schists and micaceous quartzites.)	Khomas Series Upper Schist Group. Auas Quartzite (Itabirite) Lower Schist Group.
Marble Series (Numerous marble bands with a main band over 300 metres in thickness and intercalated amphibolites, tillite)	Marble Series (Tillite horizon and marble bands, schists and itabirite).
Quartzite Series (Phyllitic quartzites and conglomeratic arkoses, mica schists).	Quartzite Series (Quartzites, arkoses and conglomerates).

The basis of correlation of the rocks of the area with those throughout South West Africa, has been suggested

by Martin. In the Kaokeveld the sedimentary iron ores or itabirites of the Damara System are always present in the tillitic zone of the Marble Series, sometimes replacing it, or occurring above or below this marker horizon. The Otjosondu area may lie within this tillite zone, but up to the present time no rock has been found which could be identified as an ancient tillite. Three possibilities may explain this. Firstly, due to the lack of extensive outcrop the tillite may be present, but as yet unobserved, in the area. Secondly, as the rocks of the area represent deposits which accumulated in the centre of the syncline it may not have been developed. A third possible explanation is that within this migmatitic zone the rock would not be readily recognised as a tillite for great alteration in appearance and mineralogical composition can be expected.

Gevers (1934), described the Lower Itabirite Horizon on Elisenhöhe and Tsatsachas as consisting of a large number of bands of itabirite varying in thickness from a few metres to 45 metres, and separated by highly ferruginous amphibole (Hornblendic-) skarn and subordinate biotite schists. The Upper Horizon is similar to the Lower, but thins rapidly until it is only a few metres wide. It appears from the description that the quartzites accompanying these rocks are generally red in colour. Deep red tints are not noted in the Otjosondu area. Furthermore, it is known that the limestone bands of the Marble Series vary greatly in thickness, but in general these rocks pass into graphitic facies. Such facies changes have not been observed in the Otjosondu area, but as mapping continues the fact that facies changes do occur will be valuable.

One other correlation which might be made is between

the itabirites of the Otjosondu area and those of the Upper Schist or Khomas Series. Factors influencing this suggestion are that the marbles are not as extensive as formerly considered; in fact, much more schist is present in the succession, and the quartzites appear to be of a similar type to the Auas Quartzites as described by Gevers.

Describing the Auas Quartzite he states: "The quartzite horizon consists of a number of lenses of fine-grained sericitic, non-conglomeratic quartzite of white, yellowish or grey colour when fresh. Deep red tints are not met with. The felspar-content is generally low and often practically absent. The quartzites are well bedded and often flaggy. They are separated by schistose rocks, in which, contrary to the rest of the Khomas Series, biotite schists are not conspicuous and strongly recede against amphibolites, amphibole and garnet schists as well as graphitic schists and phyllites. Intercalated with these schistose rocks occur mostly narrow bands of crystalline limestone in several horizons and one zone of itabirite".

The correlation of the relevant horizons is shown in Table IV.

TABLE IV.

CORRELATION BETWEEN AUAS MOUNTAINS AND OTJOSONDU AREA.

Auas Mountains.		Otjosondu Area.	
Approximate thickness (Metres)		Approximate thickness (Metres)	
7,000-8,000	Biotite schists, amphibolites, amphibole-garnet schists and graphite schists, with one or more narrow lenses of fine grained quartzite and limestone.		Probably developed to the south of Hochfels.
0 - 1,000	Ruschberg Quartzite - Fine grained sericitic quartzite.	0 - 200	Quartzite to north of Hochfels.

TABLE IV. (Contd.)

Auas Mountains.		Otjosondu Area.	
Approximate thickness (Metres)		Approximate thickness (Metres)	
300 - 400	Dark para-amphibolites and amphibole schists with subordinate biotite schists in the west with one marble band (thickness 25-30 metres). In the east (Voigtland) with two marble bands (thickness 25 and 80 metres).	over 500	Lower Schist Zone with marble.
0 - 1,800	Moltkeblick Quartzite	70	Lower Quartzite Zone.
23	Amphibolites, amphibole-graphite and biotite-schists with narrow lenses of quartzite.		
3 - 4	Itabirite (magnetite and specularite).		
20	Amphibole-, graphite- and biotite schists.		Itabirite Schist Zone.
2	Reddish and yellowish ferruginous and cherty limestone.	20	(Itabirite schist, manganese ore, amphibolitic schists).
3	Amphibole-, graphite- and biotite schists.		
2 - 3	Yellowish-white crystalline limestone.		
8 - 10	Amphibole-, graphite- and biotite schists.		
4 - 5	Greyish blue crystalline limestone with chert.		
0 - 400	Grossherzog Friedrich-berg Quartzite.	50	Upper Quartzite.
600	Para-amphibolites, amphibole-, graphite-, and biotite schists.	100	Marble Zone and Upper Schist Zone.
1½ - 2	Yellowish crystalline limestone.		

A thinning in the succession is required for the correlation to hold, but Gevers mentions the variability of the thicknesses of the members, and if deposition took place from south to north this tendency would be expected.

As mapping outside of the area increases one of the above correlations will no doubt be accepted. It is expected that the marble bands will thicken towards the west and facies change may be observed in that direction.

5. Correlation of the Granitic Rocks.

The granitic rocks of the area, which were all intruded as concordant bodies within the schists and marbles, bear a strong resemblance to those described from elsewhere in South West Africa.

The grey gneiss-granite of the area is correlated with the gneiss-granites as developed in north-western Damaraland. The red porphyritic granite and the pegmatites of the area are correlated with the "Red Granite" described by Gevers and Frommurze (1929), and the "Red Porphyritic Biotite Granite" by Gevers (1934) from the Windhoek district. Both red granites are regarded to have originated during the same period of igneous activity. The pegmatites of the area were introduced as the final stage of this granitic intrusion.

The red granites and the pegmatites of the area were thus intruded during the Salem period.

CHAPTER V.

TECTONICS.

1. Regional Structure.

a. Folding of the Damara Rocks.

In order to describe the regional structure of the area it is advantageous to divide it into two portions:-

(a) The Eastern Section - to the east of the Ebenezer-Labusrus farm boundary and its projection.

(b) The Western Section - to the west of this boundary and its projection.

The boundary is not in reality a geological one, but its choice is justified by the fact that it presents itself as the only recognizable feature in the sand-covered flat on which a dividing line can be made and, furthermore, a structural depression of major importance runs through the area close to, and parallel with, this boundary. The structure of the area as a whole is that of a highly folded southern limb of a synclinorium.

(i) The Eastern Section.

Within the eastern section three westward-plunging anticlines are superimposed on the major limb. The cores of the anticlines are formed of the Upper and Lower Quartzites and the Itabirite Schists. The synclines are formed of rocks of the Marble and Upper Schist zones. The axial planes of these folds strike approximately east-north-east and dip towards the north.

From Okamatangara the quartzites trend towards the south-west, and on the farms Uitkomst and Bosrand some complicated folds are observed in open cast workings. The quartzites then form an anticlinal nose on the farms Weltevrede, Okarutuo and Ouparakane.

A synclinal structure formed of marbles and schists occurs to the south. The flowage of these incompetent rocks is apparent on aerial photographs, and complex domal structures within the generally westward plunging syncline are observable. The Damara rocks form a synclinal nose on the farm Brakwater.

On Labusrus the intricate fold pattern which is superimposed on the major folds is well illustrated. A thickening of outcrop is observable here and, from the mining point of view, many ore bodies are exposed within a small area due to their repeated outcrop on the parallel limbs of drag folds. From Labusrus the quartzites follow the regional trend towards the Labusrus-Ebenezer boundary.

To the south of the quartzites evidence of the existence of the Lower Schist members is presented in the form of borehole intersections, surface rubble and rare outcrops. Generally the structure in these schists is obscure, as they are covered with a deep layer of sand.

As a rule, all observed plunges in the eastern area are at moderate angles (20° to 40°) towards the west. Within the marbles and schists particularly, and to a lesser extent in the quartzites, plunges in the opposite direction are probably present. The dome within the marble syncline on the farms Brakwater and Weltevrede is one structure where contra-plunges must be present. The syncline on Ongorussengo, which is formed of the Lower Quartzites, is a further example of a structure which has a plunge towards the east.

Several geologists who have visited the area have suggested the folding to be isoclinal. This was not confirmed. Although almost all recorded dips are towards the north, a definite variation is found between those measured on the northern and southern limbs of the minor

folds. The southern limbs of synclinal structures have lower dips than their northern counterparts, which have high or even vertical dips. This fact will be redescribed and explained in considering the cause and effects of folding.

(ii) The Western Section.

Just to the west of the arbitrary boundary the Lower Quartzites form the Okonjete Hill. To the west of the hill, which consists of an anticline to the north and a closed syncline to the south, rather steep lineation is observed, angles reaching 80°W being recorded. Towards the centre of the hill the plunge of lineation varies from about 8°W to 8°E, many minor culminations and depressions being present. Towards the east of the hill the plunge is towards the west, with angles seldom exceeding 20°. Further east the quartzites descend beneath the sand, and here they are cut by a large wrench fault (de Sitter, 1956). The quartzites continue westwards, and can be traced by a series of disconnected outcrops.

North of the Okonjete Hill the quartzites swing northward to form an eastward plunging anticline on the farm Ebenezer. The beds then trend east-west once again to form the Otjosondu Kop. To the north of the Kop little evidence of underlying rock type is available, and only trend lines on aerial photographs were at first used to trace the sub-outcrop of quartzites. The regional map was slightly modified here, due to the fact that evidence was subsequently obtained suggesting that after almost closing round the Otjosondu Kop the folds once again open towards the north.

It is probable that the quartzite outcrop in the extreme south-west of the area is a portion of a westward plunging structure bearing a resemblance to the eastern

section of the present map. As opposed to the general eastward plunges of the structures of the western section, the plunge on this quartzite outcrop is 30°W.

b. Faulting of the Damara Rocks.

The rocks of the area have generally relieved the stresses which they underwent by folding, as opposed to faulting; however, faults of large magnitude are also represented.

The most important types of fault in the area are those which cut the rocks at a small angle to the main stress direction, i.e. wrench-faults. One such fault, traced by magnetometric means, cuts the quartzites to the east of the Otjosondu Hill and then east of the Okonjete Hill. The orientation of this fault is repeated on Otjosondu and Ebenezer where three small dip faults having a similar orientation disrupt the beds slightly. All these faults appear to have small throws towards the south on their eastern flanks.

On the farm Brakwater a covered fault with a down-throw on the east has displaced the southern limb of the synclinal structure of this area. The northern limb appears to be unaffected.

2. General Structural Features.

a. Lineation.

The approach to the solution of the major structure of the area was achieved by first unravelling the minor structures, and only then did the clear picture of the interrelation of the large, more open folds emerge. The solution of the minor structures depended almost entirely on the use of secondary features, for almost every vestige of bedding planes has been obliterated by metamorphism. Lineation, together with the trends of the dragfolds, was the most useful secondary feature in the elucidation of

structure. Since these features will aid regional and local mapping in the manganese field as work progresses, the linear features will be described in detail.

Many structural geologists have described various aspects of lineation but few have followed specific terminology. E. Cloos (1945) integrated all the available work done on lineation up to 1945. Since then, a supplement to his Memoir has been published, E. Cloos, (1953). His nomenclature is used throughout this dissertation. The fold axis is (b), (a) is the direction perpendicular to the movement plane, and (c) is perpendicular to (ab). (See Figure 5). Cloos states that there are six kinds of lineation, due to the following causes: primary flowage, secondary flowage, rotation, intersection of planes, slippage and growth of minerals. These can be further sub-divided. (See Table V).

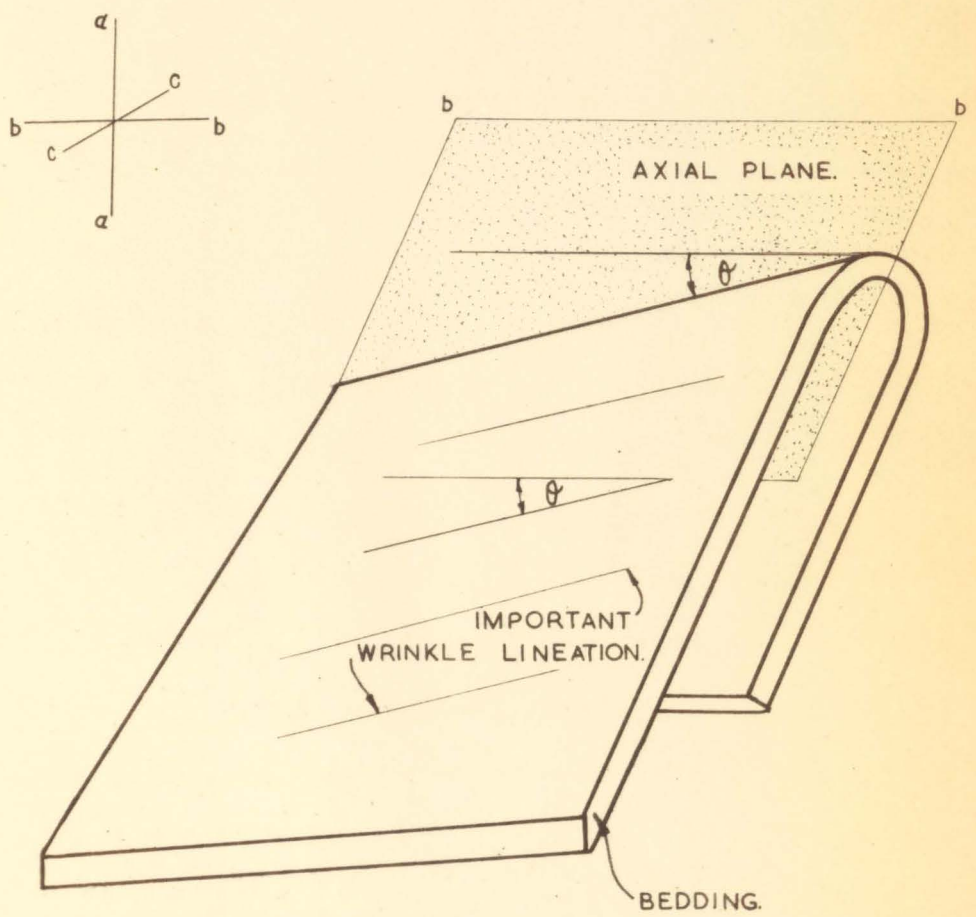
Two fundamentally different directions of movement during folding have been distinguished by Cloos, viz., the principal direction acting in this case in the (a) plane, and the subordinate one normal to the first, i.e., in the (b) or fold axis plane. The solution of the structure of the area depended chiefly on the recognition of a lineation which parallels the (b) or fold axes of the folds. This was found in the appearance of wrinkling or small folding on the bedding planes of quartzites and the intersection of shear cleavage and bedding in the case of the Itabirite Schists. The small folds and wrinkles, which are due to rotation and appear as a very distinct lineation, generally parallel the major fold axes and, providing their limitation is realized, are most useful. However, where minor folds were developed in the (a) direction, these wrinkles tend to be at right angles to the major fold axes and to follow the minor plunge direction.

FIG. 5.

ELEMENTS OF FOLDS

SHOWING

a, b & c AXES.



θ = ANGLE OF PLUNGE.

TABLE V.

SUB-DIVISION OF LINEATION (E. CLOOS, 1945).

Primary in Igneous Rocks.
Flowage.
Parallel to principal flow direction.
At right angles to principal flow direction.
Secondary in Sedimentary Rocks.
Flowage.
At right angles to (b) in principal movement direction.
Parallel to (b) in subordinate movement direction.
Rotation around (b) Axis.
Folding, flexing and drag folds.
Rolling with elongation in (b).
Intersection of S Planes.
In (b) with or without rotation.
In (a).
Slippage on S Planes.
Bedding, cleavage and joint slips.
Growth of Minerals.
In pressure shadows or (a) lineation.
(ac) joints parallel to (b).
At right angles to (b) in (ac) girdle.

Examples of the types of lineation observed in the area are now described.

(i) Lineation due to Primary Flowage.

Owing to the fact that few exposures of igneous rock were available for examination, no conclusion as to the presence of primary flowage could be made.

(ii) Secondary Lineation in the Sedimentary Members.

(1) Lineation due to flowage.

Boudinage is occasionally observed within the itabirite schists of the area. Thin quartzite beds within the schists have been drawn out and have finally yielded in tension, the gaps so formed being filled by the flowage of schist material. This phenomenon is local in extent and cannot be observed in three dimensions, with the result that its use in determining structure is limited.

The pure quartzites, schists, gneisses and the limestones all show lineation due to flowage. The difficulty in using this type of lineation in the field is twofold. In the case of the quartzites, individual quartz grains can be seen to show a definite orientation even in the hand specimen. However, both recrystallization and flowage play a part and, if the recrystallization post-dates flowage then incorrect deductions may result. Secondly, the use of quartz as an index mineral necessitates elaborate microscopic methods, and this renders it useless for a field technique.

The limestones have yielded, in many cases, completely by flowage and within these rocks at least one fixed direction can be seen with ease. (Plate III).



Plate III. An outcrop of marble showing associated surface limestone fragments. Flow cleavage is developed parallel to the hammer handle.

As a rule this is related to the fold axis but does not help in solving the problems of plunge direction.

(2) Lineation due to rotation in (b).

Folding may be considered to be the rotation of beds around an axis. In the area under discussion fold axes per se are very important linear elements and their trend is easily seen on the regional map.

The major folds when used as linear elements show a mean orientation E20°N in the horizontal plane, but they plunge eastward and westward at greatly varying angles. These angles of plunge cannot be directly studied on major structures. In the case of these folds the linear element parallels the (b) or fold axis direction, but within the area folds of smaller magnitude are found to be oriented normal to this regional (b) direction. Such folds and their accompanying development of lineation pose a problem, but it is obvious that the (b) axis of the minor cross-folds is parallel with the (a) axis of the major fold direction.

Small folds and wrinkles (less than ½" in cross-section) have been well developed on the bedding planes of the quartzites. (Plate IV). These wrinkles are very distinct and have been used throughout the area to determine the direction and plunge of the fold axes, for they parallel the axes of the minor folds upon which they are developed. Except on cross folded structures the minor folds parallel the regional (b) axis and, therefore, the lineation is in general parallel to this (b) direction but, as stated above, when the minor folds are developed in (a), this fact does not hold and they are related to the (b) axes of the minor folds only.

In the case of the itabiritic schists, the small folds and wrinkles are accompanied by an intense linear arrangement of the platy minerals, such as biotite and

specularite. (Plates V & VI).



Plate IV. Lineation in (b) on quartzite bedding planes. Wrinkle lineation developed on bedding planes is shown by straight lines. They plunge from left to right. The planes dipping towards the observer and stippled on the overlay are due to fracture cleavage. Plunge direction may be deduced to be towards the right.



Plate V. Wrinkle lineation in itabirite schist; the lineation is accompanied by an intense linear arrangement of haematite flakes.

It is important to note that, although it is possible for these wrinkles to develop on shear and fracture cleavage planes, they do not do so within the area studied. Lineation is sometimes observed on flow or fracture cleavage planes, in the form of mineral orientation and open grooving, but, where the presence of small folds is obvious, they are developed on former bedding planes.



Plate VI. Wrinkle lineation in quartzite. The lineation (which plunges at a high angle towards the right) is accentuated by the parallel orientation of haematite flakes.

(3) Lineation due to intersection of planes.

Lineations due to the intersection of planes are extremely common, and the area shows many examples. Shear and fracture cleavages are well developed in the axial zones but to measure their intersection with bedding planes is extremely difficult, for the latter planes are not obvious except where minor cremulations are already present. (Plate VII). The combination of these two types of lineation shows that in the case of shear cleavage the orientation of its trace with the bedding is in the (b) axis plane.

(4) Slippage on S-planes.

On the farm Okamatangara the quartzites show slicken-sides which are oriented at right angles to the (b) axes. They occur on horizontal bedding joints and are especially noted on the crests of anticlinal structures within the major structure. It is thus certain that the slickensiding is caused by the individual beds of quartzite sliding over one another in the manner of bent card packs. Slickensiding also appears on shear cleavage planes within the quartzites.



Plate VII. Intersection of bedding and fracture cleavage. The hammer (centre) indicates a bedding plane on which wrinkle lineation (lined) is developed. The planes (stippled) sloping towards the observer are due to fracture cleavage. The plunge of the fold axis is from left to right.

(5) Lineation due to growth of minerals.

This type of lineation is ubiquitous throughout the area. It is most important in the itabiritic schists where biotite and haematite flakes grow on the bedding and cleavage planes. Porphyritic felspar crystals in the biotite and itabiritic schists show augen structure which may represent a common linear element but, as the application of this is limited, its study was not pursued.

Growth fabric accompanies the important wrinkling effects in both quartzites and itabirite schists (Plate V), but observation of the wrinkles themselves is of greater application to the problem in hand.

(6) Lineation in (a).

Lineation in (a) has already been mentioned, but it is important to know where such lineation develops and the reason therefor. This lineation is represented in cross-fold structures and in small crenulations on bedding planes which strike at high angles to the regional (b) axis. (Plate VIII).



Plate VIII. Lineation in the (a) plane developed in quartzites. The figures are on the ore horizon which strikes from left to right on the photograph. Folds of small dimension are shown on the overlay, and although the (b) or fold axis parallels the strike of the ore horizon, a strong linear element can be seen to parallel the major (a) axis as, firstly, minor folds, and, secondly, smaller crenulations on the bedding planes of the minor folds.

They will be referred to in the description of the minor structures of ore bodies.

Their development relative to the regional structure gives a clue to their origin. They are typically developed where the beds show trends at right angles to the regional fold axes. It is therefore probable that they owe their origin to convergence of the beds near the sharp turns in the trend directions.

b. Cleavage.

It is proposed to define the various types of cleavage developed in the area, so that no confusion arises. The general cleavage, which is developed throughout the schistose rocks of the area is termed slaty cleavage when recrystallization on the cleavage planes is small. When, however, mica, amphiboles and even pyroxenes, felspars and quartz have a preferred orientation which is related to this plane, it is termed flow cleavage. Fracture cleavage is developed in the quartzites. It differs from the slaty cleavage for, although it is also roughly parallel to the axial plane, fracture-cleavage converges upwards towards the top of anticlines, whereas flow cleavage converges downwards to the anticlinal cores. (Figure 6).

(i) Flow and Slaty Cleavage.

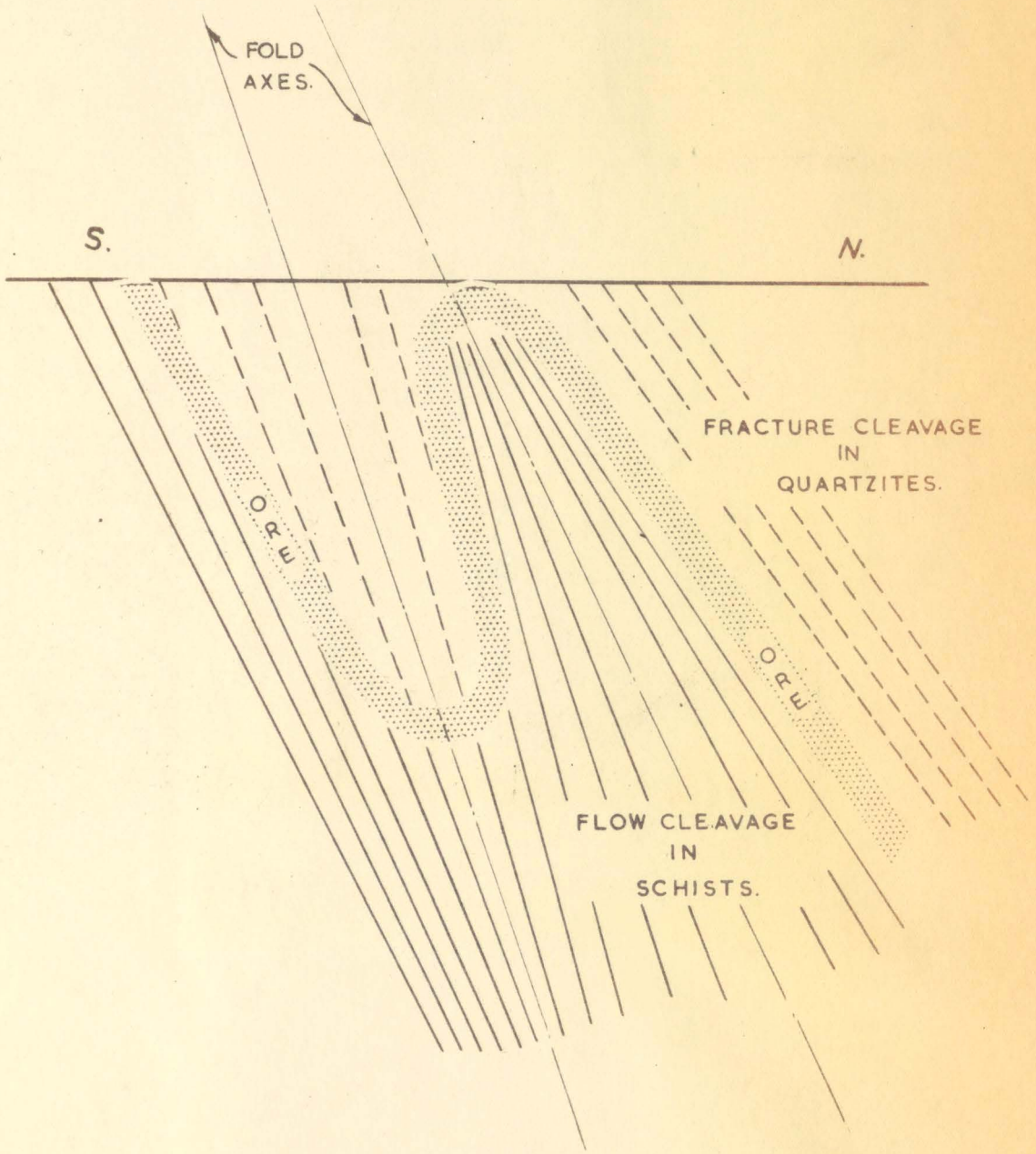
The regional cleavage of the area closely parallels the (b) axes of the folds and, since these are so compressed, the cleavage planes are generally also parallel to the bedding planes, except in the axial zones of the folds. The flow cleavage planes of the incompetent rocks of the area are often closely spaced (Plate IX), and are in many cases accentuated by the orientation of the



Plate IX. Flow cleavage in itabirite schists. The mode of break of these materials is determined by the flow cleavage planes and tension joints.

FIG. 6.

RELATIONSHIP BETWEEN CLEAVAGES & BEDDING.



platy minerals along them. The haematite of the itabiritic schists is especially prominent in this connection, but the biotite, hornblende and even pyroxenes, quartz and felspar have their long axes in the plane of easiest relief. This plane, for non-rotational stress, is at right angles to the maximum pressure. The platy minerals, therefore, present their flat sides to the pressure, and this results in a marked schistosity of the rocks.

The marbles of the area show that they have yielded to the tectonic forces by flow, and within the marbles flow cleavage planes are observed.

(ii) Fracture cleavage.

Throughout the area the quartzites display a well developed set of joints which parallel the strike of the beds and dip at steep angles towards the north (Plate X). In general, they appear to be developed on



Plate X. Fracture cleavage in a synclinal structure. The cleavage plane (stippled) dips from left to right in the centre of the photograph and thus appears to be bedding, but it is cut by a bedding plane which shows wrinkle lineation (lined).

bedding planes. However, on the tops of anticlines and the bottoms of minor synclines, they are observed to cut across the bedding planes. On careful examination, it

was found that the quartzites often display very fine planes, along which they tend to fracture. These planes parallel the joint set and are no doubt the cause of its development. Since these planes were observed to intersect bedding planes it was obvious that they were due to a secondary process which affected the rocks. Furthermore, in some specimens of haematitic quartzite, instead of the neat symmetrical corrugations normally observed on the bedding, due to the drag folding or rotation around the (b) axis, irregular crinkles were noted to be developed on these planes. Most of these were terminated by a sharp, straight plane, and it was concluded that they are due to intersections of fracture cleavage with the bedding. The sharp terminations may be likened to tiny fault scarps which have been formed to give the unique appearance of the crinkles. This phenomenon is closely related to shear or slip folding.

The presence of this shear or fracture cleavage is thus not immediately apparent, and its relationship to the flow cleavage could not be established in the axial zones. On the limbs of the fold its origin is taken to be due to concentric shear joints developed as fracture cleavage, which appeared when no further lateral shortening by folding was possible, for on these flanks the cleavage parallels the bedding.

Its presence is most important in the axial zone of folds, where it has been far too often mistaken for bedding. Figure 6 shows the relationship between the fracture cleavage and bedding. Where the fracture cleavage transsects the bedding planes and no contact with another rock is present to enable the dip to be measured, the cleavage planes have been erroneously mistaken and measured as bedding, with the result that rocks with a low dip, were never observed by previous workers in the area. (Plate X).

This phenomenon may be seen to great advantage on the Okonjete Hill where horizontal quartzites were supposed to dip northwards at high angles.

It has been the authors rule never to measure dips without being certain of what plane is being dealt with, for many wrong conclusions can obviously result from this difficulty.

c. Joints.

Four sets of joints, other than the one discussed above, which are all related to one another and to forces which affected the area, have been recognized within the quartzites. Three sets of joints are developed in the schists.

(i) Joints in the Schists.

One predominant set of joints is developed along the bedding-flow-cleavage planes on the flanks of the folds. These tend to make the rock break into long, flat fragments on blasting, but in the itabirite schists they are intersected at right angles by two sets of tension joints. This intersection causes the rock to break into pencils whose dimension parallel with bedding is larger than the other two (Plate IX). In the case of the biotite schists the two sets of tension joints do not affect the breaking of the rocks to the same extent, and thus longer "needle" types of rubble are developed.

(ii) Joints in the Quartzites.

Within the quartzites the most important joint set parallels the strike of the beds and dips at moderate to high angles towards the north. They have been mentioned before in connection with fracture cleavage. It is considered that they have their origin in the opening of planes of weakness which developed during the period in which stress caused maximum elongation to take place in a vertical plane, i.e., they were developed during the over-folding of the rocks.

Two sets of joints, which have more or less vertical dips, cut the quartzites at more or less 45° to the strike. These are considered to be shear joints which developed early in the orogenic period, when compressive forces were relieved by slight elongation in an east-west direction.

Horizontal bedding joints have been developed on the crests of anticlines (Plate XI). These owe their origin to tensile forces which were considerable during the flexing of the beds.

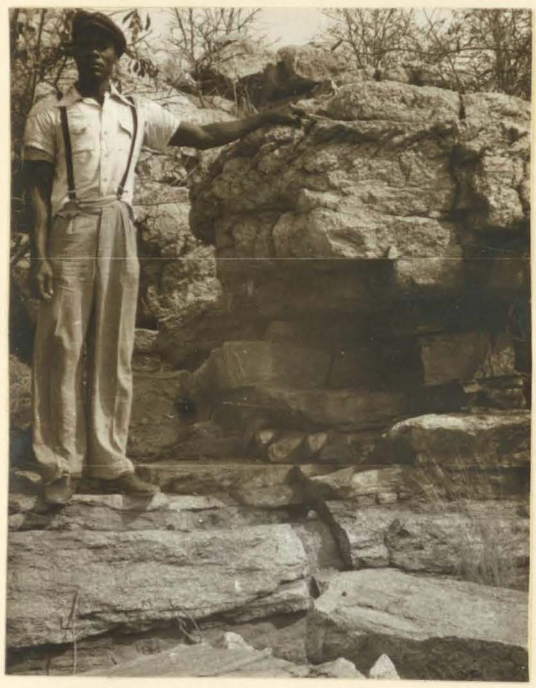


Plate XI. Horizontal joints in quartzite. The photograph was taken on the anticline which forms the Okonjete Hill. Horizontal joints here are developed parallel with the bedding.

The fifth joint set owes its origin in part to forces acting during the normal folding period, and in part to a later period of tectonic movements due to the faulting of the area. The joint fractures are oriented at right angles to the strike of the beds and are more or less vertical. They are quite different to the other joints of the area in that, instead of having a smooth plane, they

present a jagged surface giving the impression of saw teeth. (Figure 7) (Plates XII & XIII).



Plate XII. Saw-tooth joints in quartzite. The bedding joints, which dip at a small angle away from the observer, are cut by younger saw-tooth joints.

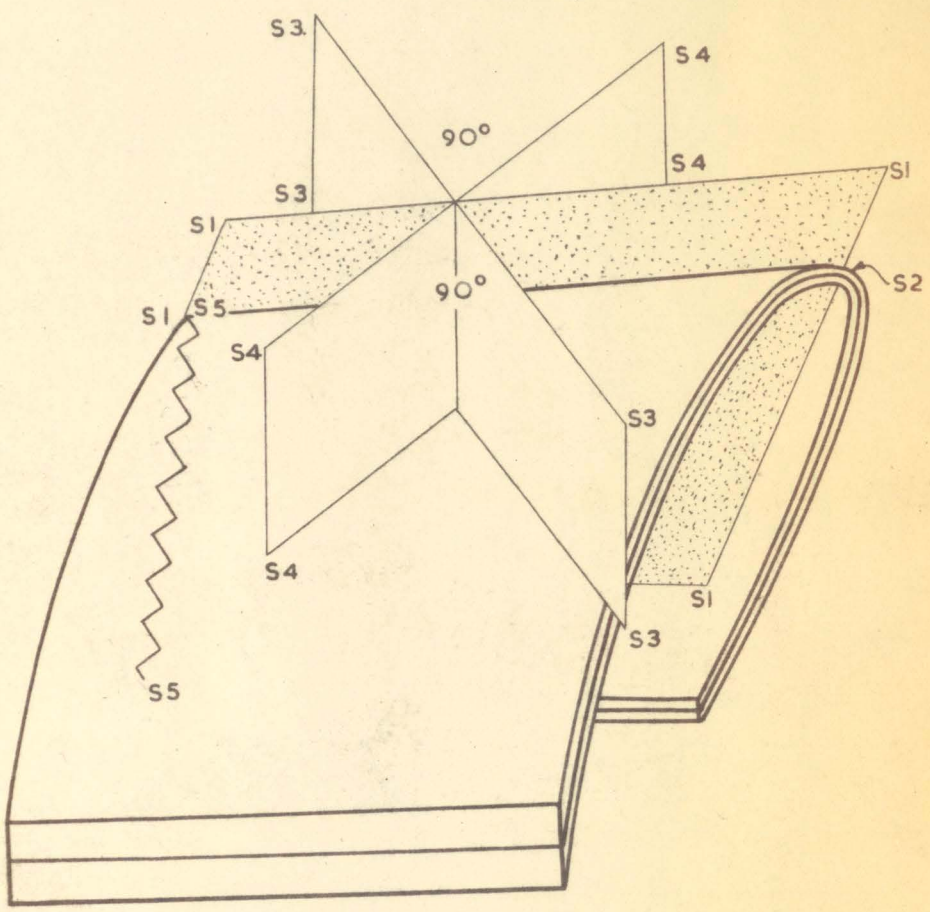


Plate XIII. Closely spaced saw-tooth joints cutting through quartzite.

The rocks have yielded to shear forces which acted in a north-south direction but, instead of a clean shear plane developing, the incipient planes already developed during the folding of the area exerted an interesting effect. Two sets of shear planes were present in the

FIG. 7.

JOINTING IN THE QUARTZITES.



S1 FRACTURE CLEAVAGE JOINTS.

S2 BEDDING JOINTS ON ANTICLINES.

S3, S4 } SHEAR JOINTS.

S5 LATER SAW-TOOTH JOINTS.

quartzites, but neither was close enough to the orientation of the later forces to cause the fractures to follow along one specific plane for any great distance; thus the rocks fractured for about an inch along one direction, and then the other plane influenced the fracture for about the same distance. This process was carried on throughout the length of the fracture and resulted in the saw-tooth appearance. The shear cleavage planes, being oriented at right angles to the later forces, exerted but little effect on these fractures. The saw-tooth joints are the youngest in age.

3. The Tectonic History of the Damara Rocks.

Throughout South West Africa the tectonic history of the Damara rocks is very complex, and structural evidence suggests that very great forces must have been active during the folding of these sediments.

The general strike of the beds in the Otjosondu Area is W.S.W.-E.N.E. This strike is by no means constant throughout the area, and it is obvious that, as throughout South West Africa, the regional forces had multi-lateral components, one of which acted in a vertical direction. This does not necessarily mean that forces causing the folding had their origin in several foci, each of which gave rise to forces acting in different directions, but that the original forces developed components which were not oriented in one specific direction nor acted in one plane. The development of such components resulted from such factors as variations in competency of beds, the limiting factor of directional elongation of the rocks subject to the stresses, and the conditions at depth, such as the nature, as well as decoluments and movements in the substratum.

Gevers and Frommurze (1929, p.50) state that"..... It is apparent that the sediments when folded were not free to

yield laterally, but experienced a considerable amount of resistance at right angles to the dominant stress, or in other words, that they were subjected to multilateral stresses. Hence the bewildering irregularity of the folds". They further state that "The resultants of these lateral stresses produced movements that are mainly directed upwards. Hence the large number of dome-like structures which characterize the plan of these ancient sediments".

Both these statements are found to be valid when applied to the Otjosondu Area. The fact that the beds were unable always to elongate themselves laterally with ease is shown by the cross-fold structures, the sudden change in the strike of beds on the major folds of the area, and the culminations and depressions, which are a feature of the tectonic pattern. Furthermore, an en echelon pattern of folding is indicated on the regional map, the axial traces of the folds of the western area being en echelon relative to the folds of the eastern area.

The mechanism of the folding which fits all the observed data within the area must now be considered. It is apparent that the rocks were unable to elongate themselves to any extent in the lateral direction, and thus tended to use the easiest direction of relief, viz., the vertical. They did this by mechanisms which were dependent on their physical properties. The limestones and schists yielded by flow, and the quartzites, due to their rigidity, by shear. Some of the limestones or marbles were able to change their form without any apparent rupture of the grains of calcite. In reality, this mechanism of limestone flow is sub-microscopic or molecular shear. The parallel flow surfaces (flow cleavage) shown by the schists were determined by the parallel arrangement of the longer axes of the unequidimensional mineral particles, such as mica

and haematite; this flowage being due to crystal growth, gliding on cleavage planes and, to a lesser extent, granulation (closely spaced shear) of the quartz and felspar. The quartzites, on the other hand, depended on macro-shear phenomena only. The shear planes developed in these quartzites are clean cuts in which the two sides have moved past each other without separation, and these rocks have thus deformed by relatively small movements along innumerable planes which are oriented almost parallel to the axial planes of the folds.

It has already been mentioned that the movements within these rocks have generally taken place along the bedding planes, except in the axial zones. The reason for this is, no doubt, that the bedding was present before folding. However, in the axial zones discordant relationship between cleavage and bedding is noted. Such folds, in which the flanks remain straight and cleavage tends to become more important in axial zones, are known as accordian folds, and are a special type of cleavage fold (de Sitter, 1956). The folds of the area show typical tension gashes in the axial zones, and the ore bodies are often cut by late vein quartz within these zones.

It is obvious from what has been said that folding has taken place at great depth where confining pressures were high. Both the elastic properties of the rocks as well as plastic deformation played a part in governing the type of folding, for the elastic strain was gradually transformed into a permanent strain along the slip planes, i.e., the folding took place in the elastico-viscous field of the strain diagram.

Faults associated with the folds are probably late tectonic in age. They are typically of the wrench fault type, and confirm the fact that the rocks were deeply buried during folding.

The granite tectonics could not be studied in detail, due to lack of outcrops. However, it is apparent that most of the large pegmatite dykes show a perfectly concordant relationship to the folded beds. Smaller off-shoots of these dykes, however, are cross cutting. The dykes were probably intruded during the last phase of tectonic activity.

CHAPTER VI.

PETROGRAPHY.

1. Methods.

The rocks were studied by means of thin sections and, where necessary, they were crushed and determinations were conducted on this material. Axial and extinction angles together with other necessary optical constants were measured on a five-axis universal stage. Refractive indices are quoted for sodium light except where otherwise stated. The refractive indices of liquids were checked with a Leitz- Jelly refractometer.

The rocks are described firstly according to their zonal position, but within any zone the rock types appear in genetic groups for ease of reference, e.g. calcareous members of the Lower Schist Zone are described together. The petrography of the ore horizons will be described with the mineralogy under Economic Geology.

2. Rocks of the Damara System.

(a) Lower Schist Zone.

Specimen No. 101 A. Biotite - plagioclase - quartz granulite.

Macroscopic: In the hand specimen the rock appears slightly foliated. It consists of dark biotite and pink and white felspar together with quartz.

Microscopic: Texture: Granoblastic.

The rock consists of highly pleochroic biotite altering to chlorite, set in a groundmass of plagioclase and quartz. A few flakes of green hornblende are present.

The plagioclase, which is generally oligoclase, is crowded with epidote and apatite. The saussuritization of the plagioclase and the formation of chlorite from the biotite are due to retrograde metamorphism.

Specimen No. 101 B. Biotite - plagioclase-quartz gneiss.

Macroscopic: The hand specimen appears almost exactly the same as 101 A but the foliation of the rock is more definite.

Microscopic: Texture: Lepidoblastic.

The minerals in this section are identical to those in the former, but the biotite is oriented in one direction, thus giving rise to the marked foliation of the rock.

Specimen No. 100. (Plate XIV). Quartz - hornblende - labradorite schist.

Macroscopic: The rock is greenish-black in colour and shows a rough foliation. No minerals can be identified in the hand specimen even with the aid of a lense.

Microscopic: Texture: Nematoblastic.

The rock consists of highly pleochroic green hornblende with quartz and felspar. The quartz, which makes up about 50% of the rock, adds to the texture by showing a preferred orientation parallel to the long axes of the hornblende. The felspar, which is andesine and labradorite, is often set in larger quartz crystals. No orthoclase is observed, and suassuritization has not occurred.

Accessory minerals include magnetite, apatite and rounded zircon.

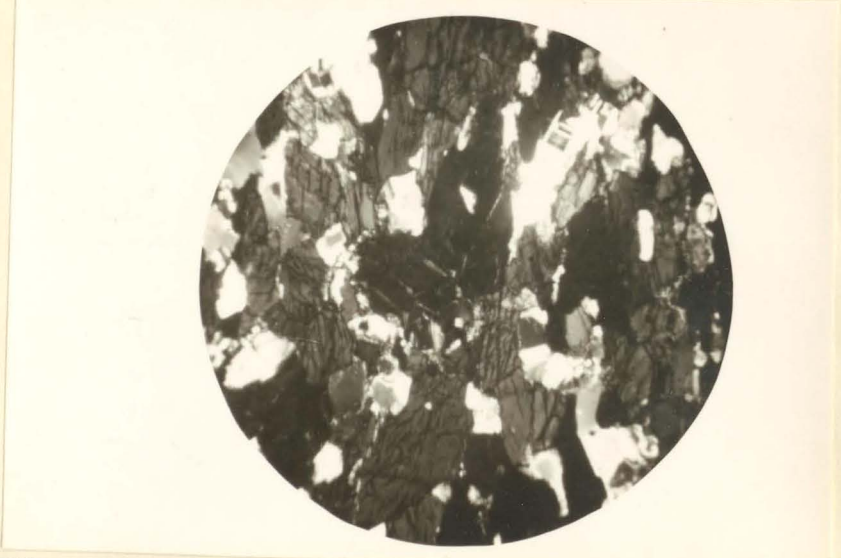


Plate XIV. Quartz - hornblende - labradorite schist (No. 100). Highly pleochroic hornblende (H) showing nematoblastic texture with labradorite (Lab) and quartz (Qz).
(Crossed Nicols; x30)

Specimen No. 96. Hornblende amphibolite.

Macroscopic: The rock is a compact dark green amphibolite.

Microscopic: Texture: Strongly Nematoblastic.

The rock is seen to consist of highly pleochroic green hornblende with almost equal proportions of quartz and felspar. Andesine is the dominant plagioclase and orthoclase appears to be absent.

The quartz and felspar do not appear to have assumed any particular orientation but merely fill the interstices between the abundant and perfectly oriented nematoblasts of hornblende.

Apatite appears as an accessory mineral.

Specimen No. 93. Diopside granulite.

Macroscopic: The rock, which is intensely hard and fine-grained, is grey-green in colour. Individual minerals cannot be recognised in the hand specimen.

Microscopic: Texture: Decussate.

The rock consists almost entirely of colourless diopside crystals. Two sizes, which may represent two generations, are present. The large crystals often enclose a little calcite, but this mineral may have a secondary origin. A few plagioclase crystals are present. and they are aligned between the coarse crystals and the fine. A grain which appears to be vesuvianite is present in the slide.

Specimen No. 136. Diopside - plagioclase granulite.

Macroscopic: The rock is similar to No. 93 but is not so hard and is lighter in colour.

Microscopic: Texture: Pophyroblastic.

Porphyroblasts of colourless diopside are developed with quartz and plagioclase. The plagioclase, which is andesine to labradorite, together with quartz forms the groundmass in which a small quantity of bronze mica is

present.

Apatite appears as an accessory mineral.

Specimen No. 93 A. (Plates XV & XVI). Diopside - quartz - plagioclase - grossularite granulite.

Macroscopic: This rock is dark grey - green and intensely hard. Foliation is not apparent.

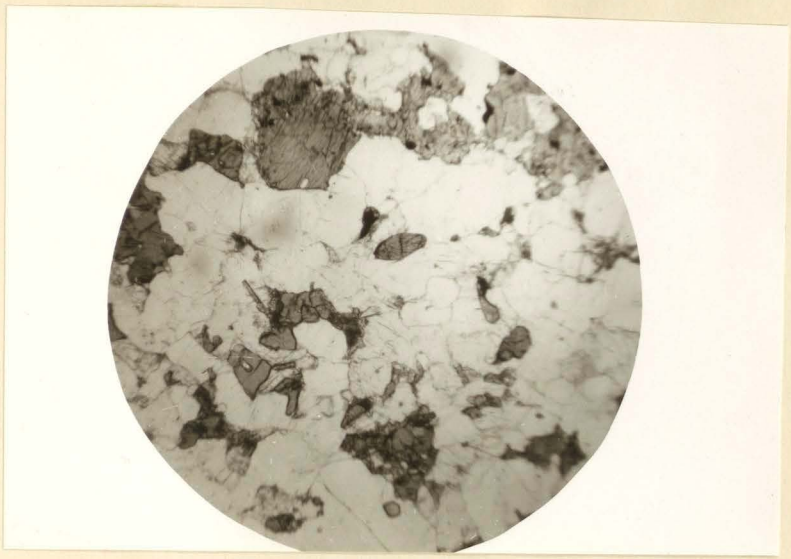


Plate XV. Diopside - quartz - plagioclase - grossularite granulite (No. 93A). Granoblastic diopside (D) quartz (Qz) and plagioclase (Pl) enclose sphene (Sp) and apatite (Ap). Grossularite (Gr) is present. (Plane Polarized light: x 30).



Plate XVI. As Plate XV.
(Crossed Nicols; x 30)

Microscopic: Texture: Granoblastic.

The rock consists of almost equal amounts of granoblastic diopside, plagioclase and quartz.

The plagioclase is andesine to labradorite. Grossularite is present in a form which suggests that it is pseudomorphous after chlorite. A little interstitial calcite is also present. An abundance of sphene wedges are present both in felspar and femic minerals. Scapolite is seen as rare crystals in the section. Apatite is an accessory mineral.

Specimen No. 99A. (Plates XVII & XVIII).
Diopside - scapolite granulite.

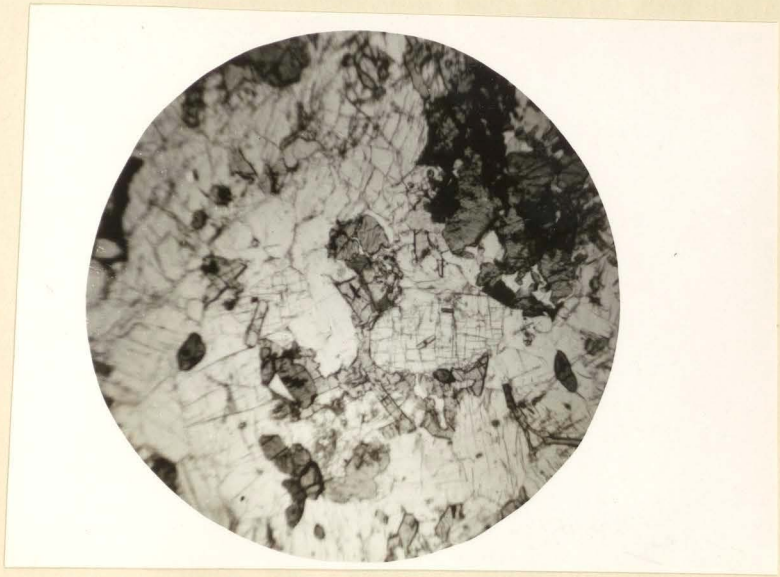


Plate XVII. Diopside - scapolite granulite (No. 99A) Granoblasts of diopside (D) and scapolite (S) accompany small but abundant crystals of sphene (Sp) and apatite (Ap).
(Plane Polarized light; x 30).

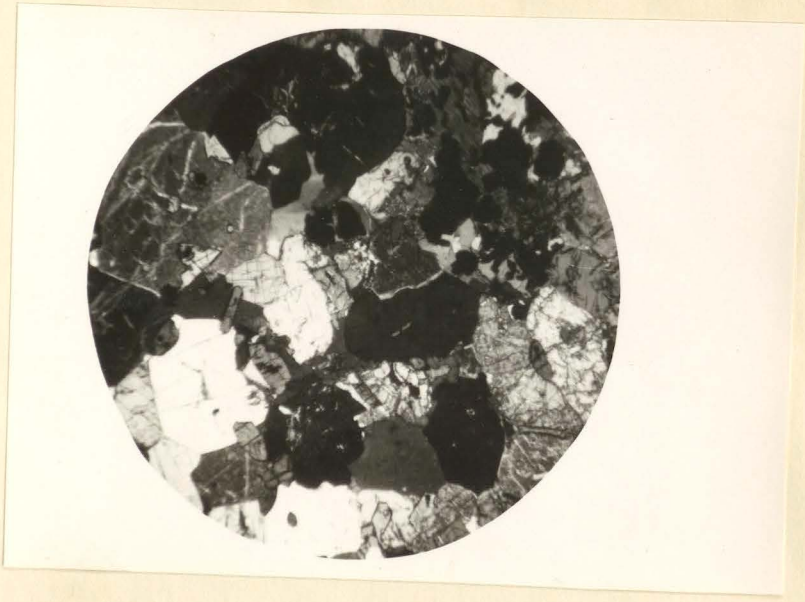


Plate XVIII. As Plate XVII.
(Crossed Nicols; x 30).

Macroscopic: As contrasted with the former diopside-bearing varieties this rock is soft and weathers rapidly. In it individual minerals are easily recognised on weathered surfaces.

Microscopic: Texture: Granoblastic.

The rock consists of granoblasts of diopside, which is altering to actinolite, and scapolite in which rare plagioclase remnants are present. In the scapolite sphene is seen to be altered to titanium oxides along parting planes. Apatite is present.

The refractive indices of the scapolite are

$$w = 1.585 \ (\pm 0.005)$$

$$e = 1.555 \ (\pm 0.005)$$

These suggest that the scapolite has a high meionite content.

Specimen No. 143. Graphitic marble.

Macroscopic: This specimen was collected from the marble horizon in the Lower Schist Zone. It is moderately coarse grained with dark graphite flakes.

Microscopic: Texture: Crystalline.

The rock shows recrystallization of the calcium carbonate. No calc-silicate minerals are observed in the section, thus indicating the rock to have been very pure.

Specimen No. 27. (Plate XIX). Garnetiferous - quartz - felspar granulite.

Macroscopic: This specimen is a pinkish quartz-felspar rock with little apparent gneissosity. Clots and rosettes of biotite are present. In some portions of the rock the quartz is seen to be concentrated into lenses.

Microscopic: Texture: Porphyroblastic, pseudo-cataclastic.

The rock consists of large crystals (porphyroblasts) of perthite formed from microcline, set in a quartz-felspar groundmass. The ex-solved sodic material

occurs as blebs and patches. Definite replacement veins of sodic felspar are also present in the porphyroblasts, and these have their origin in the mobilization of the exsolved material under the shear conditions. On the edges of the perthitic porphyroblasts myrmekite is observed; it is considered that the development of the myrmekite is the forerunner of the assimilation process by which the groundmass is replaced by the porphyroblasts.

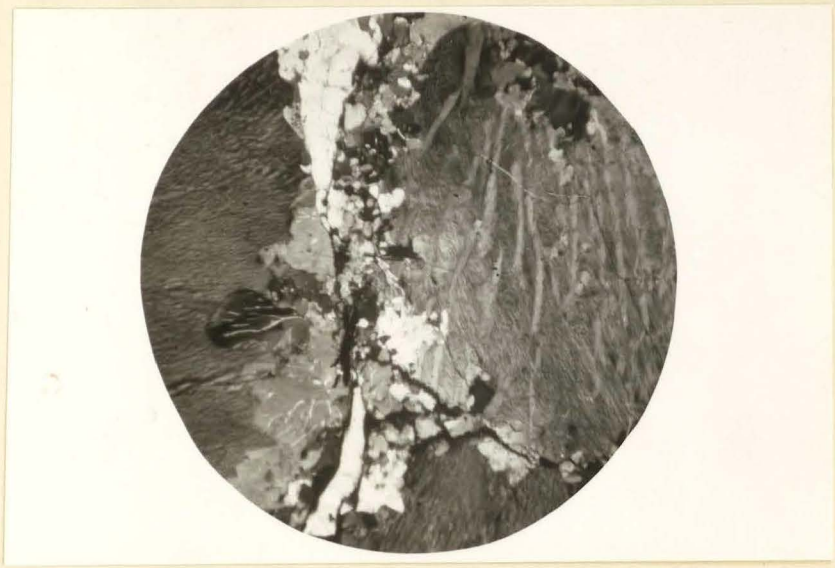


Plate XIX. Garnetiferous quartz - felspar Granulite (No.27). The former microcline (Mi) porphyroblasts which are now perthitic (P) are surrounded by a pseudo-cataclastic quartz and felspar groundmass. Sodic felspar (Ab) occurs as veins within the porphyroblasts and replaces them in part with the formation of myrmekite (Mk). (Crossed Nicols; x 30).

The lenses and streaks which surround the perthites consist of a fine grained mixture of quartz and twinned plagioclase (Ab_{10} to Ab_7An_3). Within these fine grained lenses garnets (almadine) are developed.

A little pleochroic biotite is present in the finer bands, and this is accompanied by braids of sillimanite needles which sometimes enter the perthite porphyroblasts, showing that the latter grew at the expense of the groundmass.

Quartz is present and shows a coarse lenticular

texture in the groundmass.

Specimen No. 28. Quartz-felspar granulite.

Macroscopic: This specimen is a white quartz-felspar rock with segregated biotite rosettes.

Microscopic: Texture: Granulitic.

The rock consists of coarse crystals of oligoclase and microcline which is developing perthitic texture. In the oligoclase, groundmass remnants are present, suggesting replacement of the groundmass by this mineral. The groundmass consists of a mixture of quartz, microcline and muscovite showing a pseudo-cataclastic texture.

Specimen No. 29. (Plates XX & XXI). Garnetiferous quartz-felspar-sillimanite granulite.

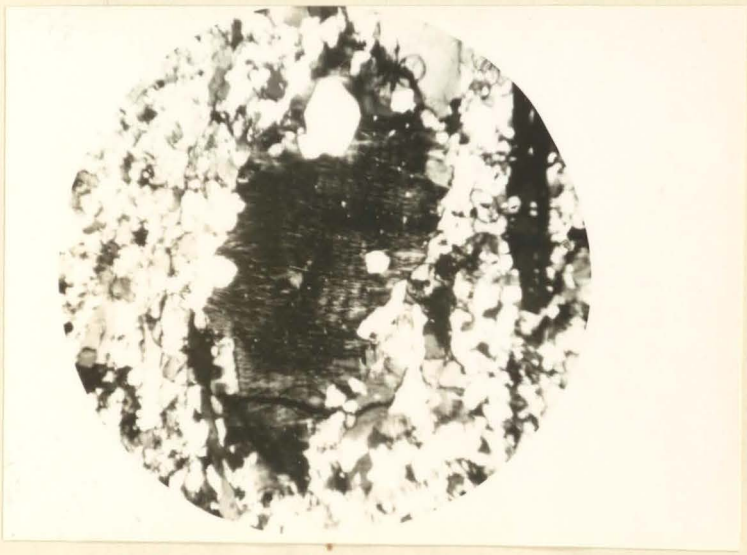


Plate XX. Garnetiferous quartz-felspar-sillimanite granulite (No. 29). A microcline (Mi) porphyroblast is growing at the expense of the quartz-felspar groundmass.
(Crossed Nicols; x 30).

Macroscopic: This specimen is a white gneissose rock in which grey biotite is present and large garnets are visible in the hand specimen.

Microscopic: Texture: Granulitic, porphyroblastic.

This rock resembles specimen No. 27. It consists of porphyroblasts of microcline on the edges of

which myrmekite is developed. The microcline is becoming perthitic. The groundmass consists of quartz, orthoclase, microcline and untwinned plagioclase. Biotite and a more obvious development of almandine and sillimanite is noted.

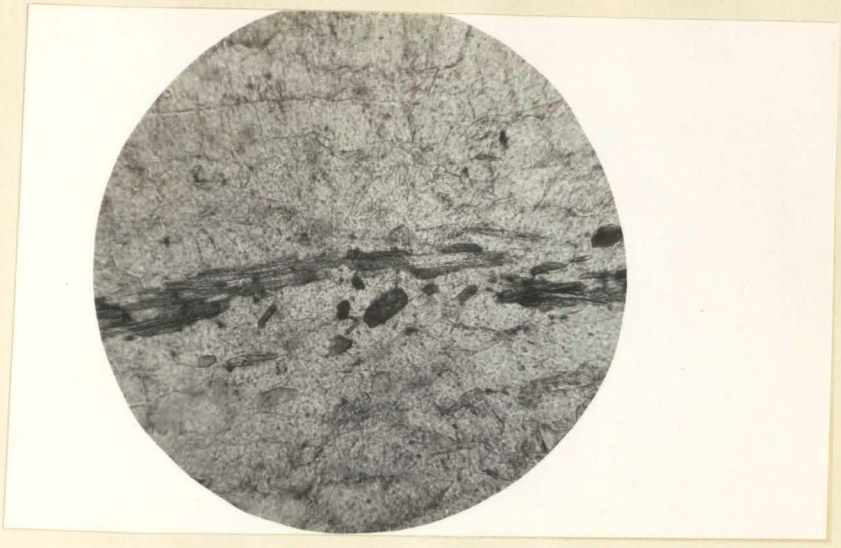


Plate XXI. Garnetiferous quartz - felspar - sillimanite granulite (No. 29).
Needles of sillimanite (Sl) accompany biotite (Bi) and quartz ribbons.
(Plane Polarized light; x 80).

(b) Lower Quartzite Zone.

Specimen No. 135. Quartzite.

Macroscopic: The quartzite is a pure, white, coarsely crystalline rock in which occasional grey-black haematite flakes are observed.

Microscopic: Texture: Quartz Mosaic.

The rock consists of over 90% quartz which forms an interlocking mosaic. The other 10% consists of white mica and a little felspar. The quartz grains show strain shadows which do not cross the grain evenly on rotation, but do so in a way that suggests that the large grains are made up of smaller grains which show no obvious boundaries, and which are not yet in complete optical continuity.

Heavy minerals were separated from the light residue by means of bromoform. A fact which is worthy of note, for this rock type as well as rocks throughout the area,

is that magnetite is rather rare. Ilmenite is the most abundant magnetic mineral in the quartzites. Small euhedra of haematite are present. The most abundant of the translucent minerals is zircon, both rounded and euhedral types being present. Apatite, epidote, rutile, garnet, tourmaline, brookite and andalusite are also present in the heavy fraction. An amphibole (20^{o} Extinction) and a single grain of fluorite were present as rare accessories.

(c) Itabiritic Schist Zone.

Specimen No. 53. Biotite - itabirite Schist.

Macroscopic: The rock consists of bands of haematite in a quartz and biotite groundmass. The rock shows a definite schistosity.

Microscopic: Texture: Lepidoblastic.

The slide consists of lepidoblastic biotite and haematite set in a quartz matrix. Some twinned plagioclase (andesine) accompanies the quartz. The haematite crystals parallel the biotite flakes or occur as small crystals within the quartz. Rare orthoclase, accompanied by myrmekite, is observed.

Apatite and zircon occur as accessory minerals.

Specimen No. 57. (Plate XXII). Hornblende - haematite schist.



Plate XXII. Hornblende - haematite schist.
Hornblende (H) and haematite (He) together with quartz (Qz) form a schistose rock.
(Plane Polarized light; x 30).

Macroscopic: This rock, which shows definite foliation, is dark green in colour.

Microscopic: Texture: Nematoblastic.

The slide consists of green hornblende and haematite crystals in a groundmass of twinned plagioclase (andesine to oligoclase) and quartz. The femic minerals show a marked orientation, and both these and the quartz and felspar are charged with minute apatite crystals.

Specimen No. 84. Augen-gneiss.

Macroscopic: The rock consists of an abundance of biotite flakes together with haematite. Accompanying these, large "augen" are formed by felspars, these giving the characteristic texture.

Microscopic: Texture: Porphyroblastic.

Large porphyroblasts of orthoclase which are slightly perthitic are present with biotite and haematite. The orthoclase has replaced the plagioclase-quartz groundmass normally observed in the rock.

Apatite is an accessory mineral.

Specimen No. 143. Itabirite schist.

Macroscopic: The rock consists of bands of pure quartz and haematite.

Microscopic: Texture: Banded.

The rock is seen to be typically banded under the microscope. Haematite occurs either in elongated flakes or in minute crystals enclosed in the quartz grains. Felspar is absent from the quartz bands.

Specimen No. 138. Pegmatite - schist Contact.

Macroscopic: The specimen was taken at the contact of itabiritic schist and pegmatite.

Microscopic: Texture: Pegmatitic and schistose.

Orthoclase is observed to be replacing plagioclase in the pegmatitic portion of the slide and a large amount of plagioclase is left as remnants within the

orthoclase. The schistose portion consists of a pyroxene (augite) with haematite, sparse biotite, orthoclase and apatite.

(d) Upper Quartzite Zone.

Specimen No. 145. Haematitic quartzite.

Macroscopic: The rock is white in colour and coarse grained. Haematite flakes are recognisable in the hand specimen.

Microscopic: Texture: Banded.

The rock is a banded haematitic quartzite and may be considered the intermediate stage between itabirite and quartzite. The haematite is either present in regular bands within the quartz mosaic or included within the quartz grains themselves. The quartz has irregularly sutured borders. No felspar is present in the section but apatite is seen to be an accessory mineral.

Specimen No. 37. Biotite - garnet quartzite.

Macroscopic: The rock is greyish in colour and consists of quartz grains in which are set biotite flakes and small bright red garnets.

Microscopic: Texture: Granoblastic.

The rock consists of an interlocking quartz mosaic in which biotite tends to be present in a definite orientation. Rare plagioclase felspar (albite) is observed. Garnets (Almandine) carrying quartz inclusions are abundant.

Specimen No. 70. (Plate XXIII). Plagioclase - quartz granulite.

Macroscopic: The rock is pink in colour and made up of quartz and felspar. A little biotite appears in the hand specimen.

Microscopic: Texture: Granulitic.

The rock consists dominantly of quartz, plagioclase (oligoclase to andesine), and orthoclase.

Some microcline is present, but it is in the process of reverting to orthoclase. Within the plagioclase felspars a myrmikitic intergrowth is often noted at the peripheral contact with the potash felspar. Bot the plagioclase and the orthoclase show some replacement by albitic rims. These reaction and replacement features will be further discussed under the petrology of the Damara Rocks. A little biotite is present, as is zircon.



Plate XXIII. Plagioclase - quartz granulite (No. 70). At the periphenal contact of orthoclase (Or) with plagioclase (Pl) myrmekite (Mk) has formed. It is obviously late in origin for its formation postdates twinning of the plagioclase.
(Crossed Nicols; x 80).

Specimen No. 132. (Plate XXIV). Microcline granulite.

Macroscopic: The rock is pink in colour and consists of bands of black biotite set within felspathic material. Quartz is not easily observable without the aid of a lense.

Microscopic: Texture: Porphyroblastic.

The rock is predominantly formed of microcline which is tending to form large porphyroblasts together with highly serrated quartz grains. The felspars other than microcline are often turbid and sericite, which is in the process of forming muscovite, is present within them. The muscovite in turn appears to be forming biotite,

the latter mineral having a definite preferred orientation.

A little sphene and ore are present.

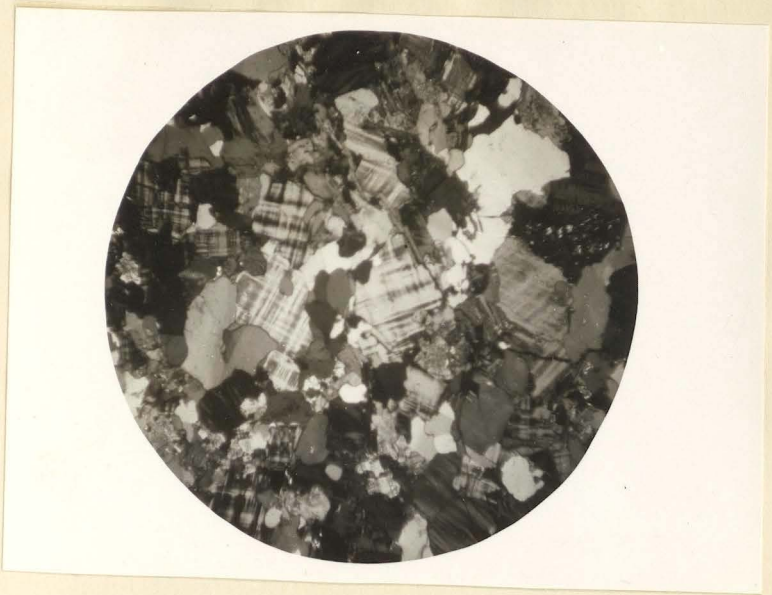


Plate XXIV. Microcline granulite (No. 132)
Crosshatched microcline (Mi) is replacing the quartz and felspars which form the groundmass of the rock.
(Crossed Nicols; X 30)

Specimen No. 141. (Plate XXV). Microcline granulite.

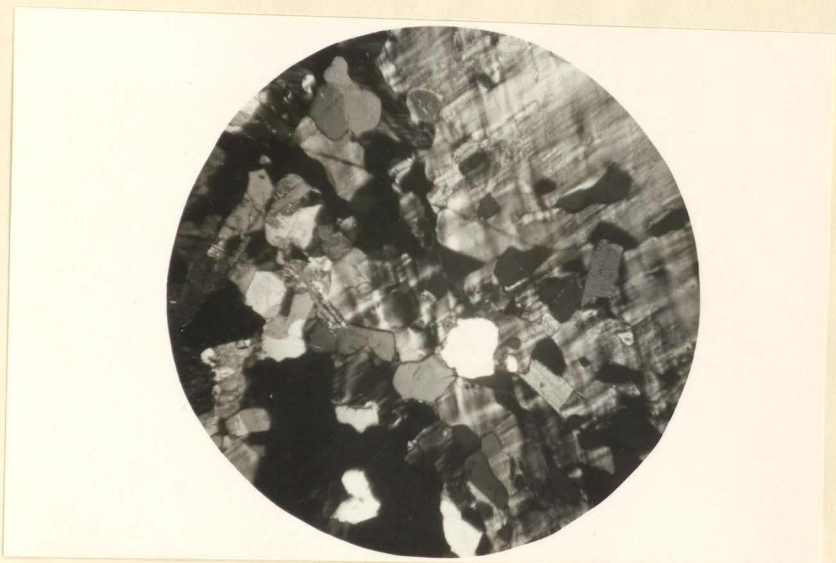


Plate XXV. Microcline granulite (No. 141).
A microcline (Mi) porphyroblast enclosing biotite (Bi) flakes and rounded quartz (Qz). Some preferentially oriented quartz blebs occur within the porphyroblast.
(Crossed Nicols; x 30).

Macroscopic: This rock is similar to No. 132, but the biotite is less well oriented, and larger porphyroblastic felspars are observed.

Microscopic: Texture: Porphyroblastic.

The rock consists of large porphyroblasts of microcline which enclose rounded quartz grains and even biotite flakes. Muscovite and a little biotite is present in between the porphyroblasts.

(e) Marble Zone.

Specimen No. 62. Marble.

Macroscopic: The rock is a marble, the calcite crystals being up to ¼ inch in length. Graphite flakes are present, and the rock emits a distinct sulphurous odour when struck. A great deal of difficulty was encountered in the preparation of the slide, since the material shatters on heating, due no doubt to the volume increase undergone by the gaseous inclusions.

Microscopic: Texture: Crystalline.

The rock appears in section to be monomineralic, as no graphite remains after grinding. The calcite rhombs are undistorted and generally twinning is absent.

Specimen No. 65. (Plate No. XXVI). Tremolite marble.

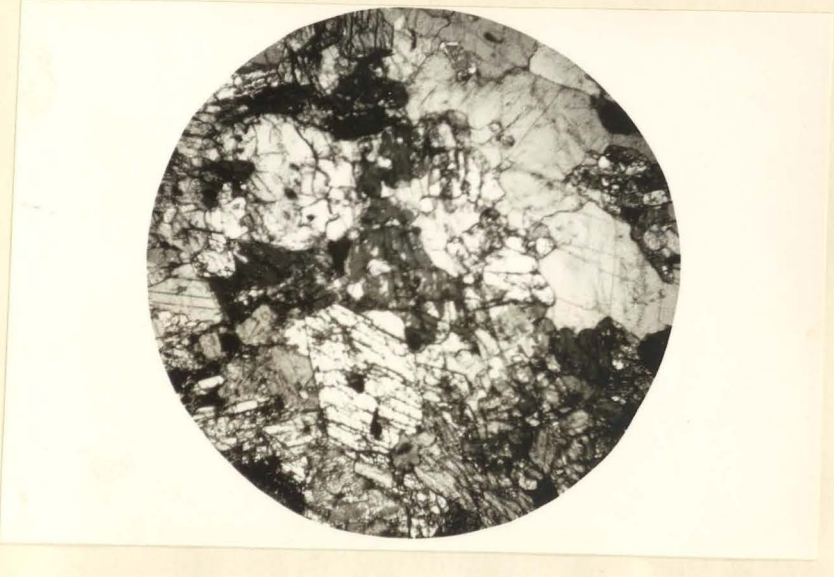


Plate XXVI. Tremolite marble (No. 65).
An abundance of termolite (T) is present in the slide together with calcite (Ca).
(Plane Polarized light; x 30).

Macroscopic: This rock consists of coarse calcite rhombs together with a large amount of red, pink and brown silicate minerals. A little white mica is observable in the hand specimen.

Microscopic: Texture: Decussate in part.

Microscopically the rock is observed to be made up of an abundance of tremolite needles set in calcite in places, but in others forming a dense aggregate of prisms.

Specimen No. 63. (Plates XXVII & XXVIII).

Periclase - brucite marble (Predazzite).

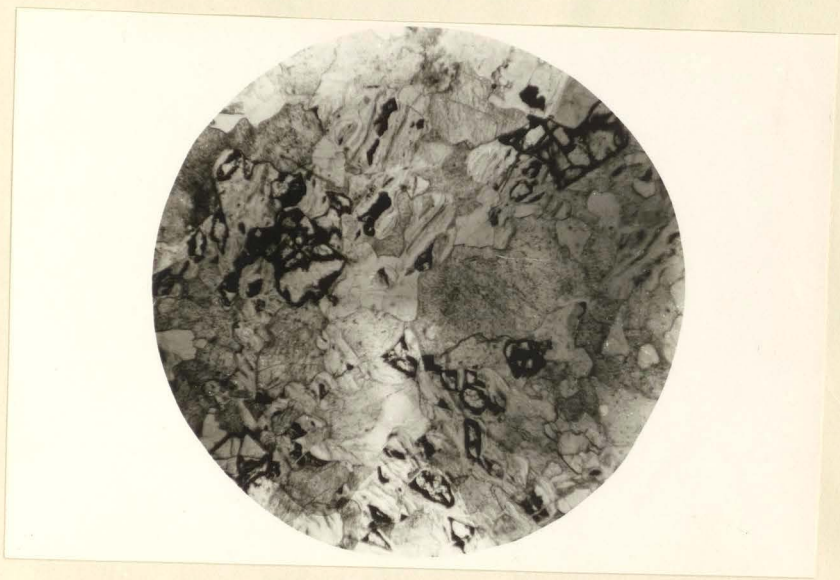


Plate XXVII. Predazzite (No. 63).
Brucite (Br) crystals which are altered to periclase (Pe) in calcite (Ca).
(Plane Polarized light; x 30).

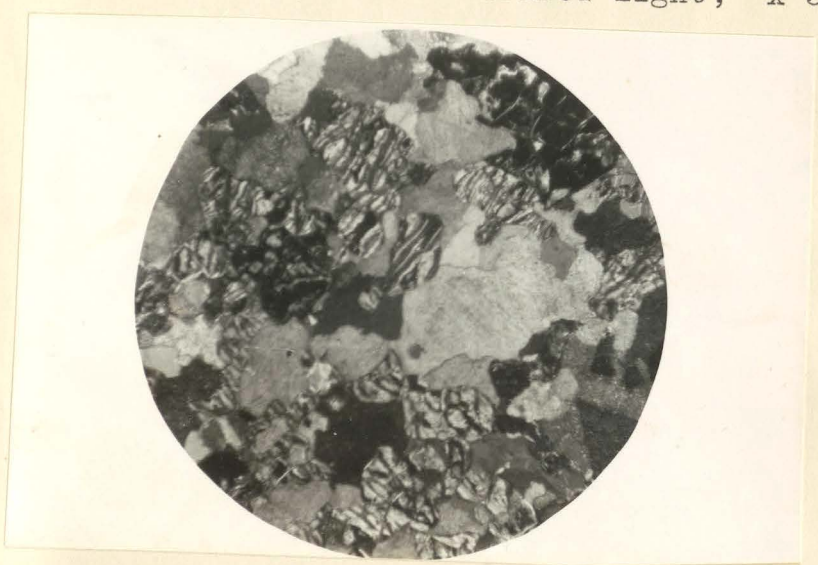


Plate XXVIII. As Plate XXVII. (Crossed Nicols; x 30).

Macroscopic: This is a white, fine grained marble with slight green tinge.

Microscopic: Texture: Crystalline in part.

The rock is composed of periclase, brucite and calcite. The periclase shows idioblastic habit, but has suffered change by hydration, being replaced by flaky brucite in such a way that islands of periclase alone remain unaltered. It appears that the rock must be considered to be a predazzite rather than a pencatite.

Specimen No. 66. Brucite marble.

Macroscopic: This specimen is a fairly soft pinky marble.

Microscopic: Texture: Crystalline in part.

This specimen is similar to No. 63 but hydration has progressed to a further stage and no periclase remains. The rock originated from a dolomitic limestone.

Specimen No. 56. Idocrase marble.

Macroscopic: The hand specimen is seen to be made up of fairly coarse calcite rhombs together with an abundance of a harder pale yellow mineral.

Microscopic. Texture: Crystalline.

In thin section the rock is observed to be made up of coarse calcite rhombs together with colourless crystals of wollastonite in rosetted arrangement The yellow mineral observed in the hand specimen is idocrase which occurs as small prisms throughout the section. A single shattered grain of grossularite, accompanied by tremolite, is present. A little ore, probably magnetite, is observed.

Specimen No. 67. Diopside granulite.

Macroscopic: The specimen is an intensely hard reddish-brown calc-silicate rock which on weathering forms definite outcrop as opposed to the marbles within which it occurs.

Microscopic: Texture: Decussate.

Microscopically the rock consists of a dense intergrowth of diopside crystals with varying amounts of calcite. A white mica is observed to be present.

Specimen No. 76. (Plates XXIX & XXX).
Recrystallized Arkose.

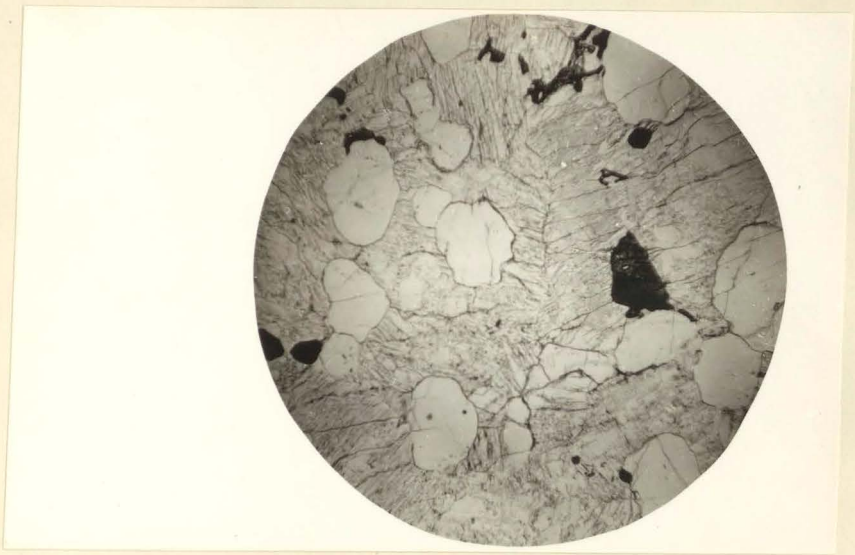


Plate XXIX. Recrystallized Arkose (No. 76).
The slide consists of rounded quartz (Qz) grains within perthitic (P) and anti-perthitic (AP) felspars. Sphene (Sp) is present in the section.
(Plane Polarized light; x 30).

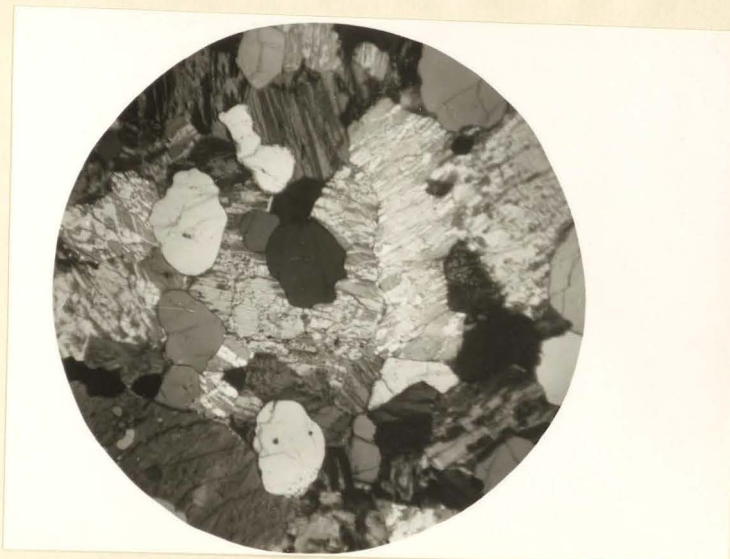


Plate XXX. As Plate XXIX.
(Crossed Nicols; x 30).

Macroscopic: The rock is made up of rounded quartz grains and felspar.

Microscopic: Texture: Recrystallized.

This rock is observed to consists of perfectly rounded quartz grains set in felspars which are perthitic and anti-perthitic. It is almost impossible to decide which is host and which is guest, however, it appears that the sodic felspar replaces the potassic. Sphene, which appears to have been formed from original ilmenite grains, is present in the slide.

Specimen No. 142. Microcline granulite.

Macroscopic: The hand specimen appears to be made up of equal amounts of quartz and felspar. Biotite is noted in the hand specimen.

Microscopic: Texture: Granulitic.

The rock consists dominantly of microcline and highly serrated quartz grains. The microcline appears to be in the process of replacing oligoclase felspar. Within the plagioclase myrmekitic texture is observed. Biotite and muscovite are present in almost equal amounts. Sericite is present in bands within the oligoclase.

(f) Upper Schist Zone.

Specimen No. 144. Biotite - plagioclase - quartz schist.

Macroscopic: Macroscopically the rock is seen to consist of biotite, pink and white felspar and quartz. It shows strong foliation.

Microscopic: Texture: Leipidoblastic.

The rock consists of highly pleochroic biotite, which in some instances shows alteration to chlorite, in a groundmass of oligoclase and quartz. Epidote and apatite appear as accessory minerals.

3. Granites and Pegmatites.

Specimen No. 80. (Plates XXXI, XXXII & XXXIII). Red Porphyritic Granite.

Macroscopic: The rock is a porphyritic, coarse grained pink granite which carries an abundance of biotite.

The phenocrysts of orthoclase are sometimes as large as 2 inches x 1 inch, and these give the rock a very striking appearance.

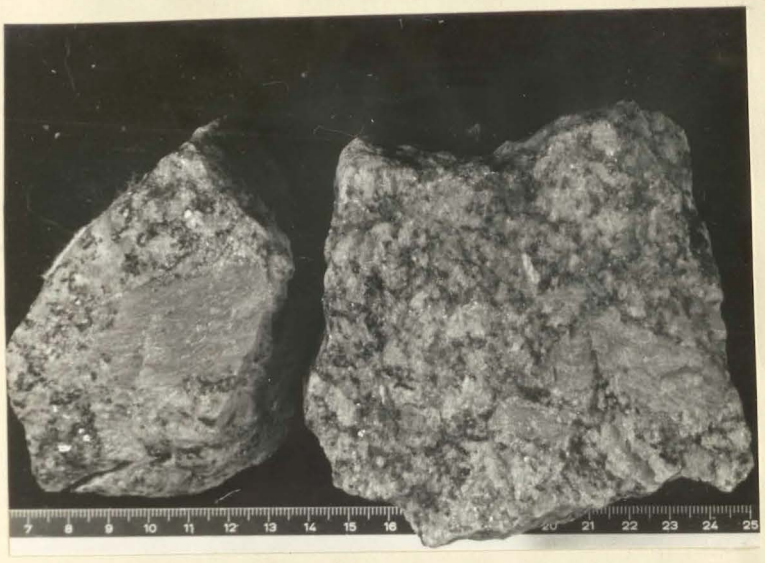


Plate XXXI. Red porphyritic granite (No. 80).
The photograph shows typical hand specimens of the porphyritic biotite-granite. The large porphyroblasts of orthoclase should be noted.
(Scale in centimetres).

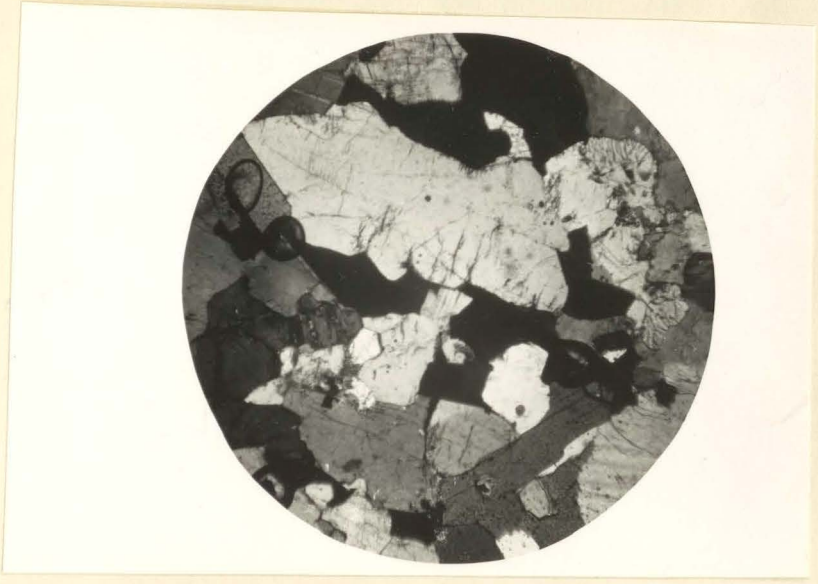


Plate XXXII. Red porphyritic granite (No. 80).
Typical orthoclase (Or), biotite (Bi), quartz (Qz) granite from Bosrand.
(Crossed Nicols; x 30).

Microscopic: Texture: Granitic, porphyritic.

The most important feature of this rock is that whereas microcline is almost invariably developed in the granulitic and gneissic rocks of the area,

it is absent from the Bosrand Granite. The rock consists of almost equal amounts of orthoclase and oligoclase felspar together with biotite and quartz. Myrmekitic intergrowths are observed at the contacts of the orthoclase and plagioclase felspars.

The usual accessory minerals, viz., apatite, zircon and rutile, are present in the biotite.

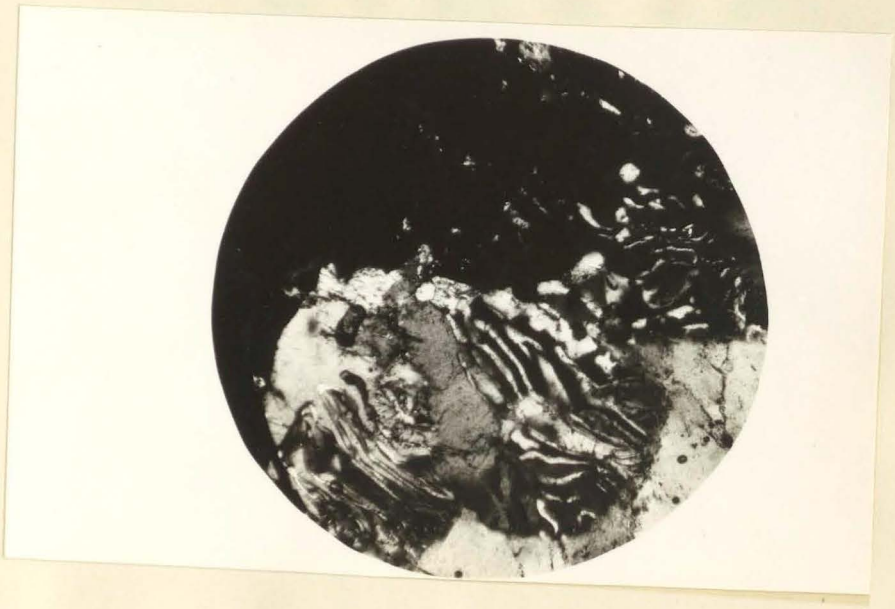


Plate XXXIII. Red porphyritic granite (No. 80). Myrmekitic intergrowth of quartz (Qz) and sodic felspar (extinguished) at the contact of oligoclase (Ol) phenocryst. (Crossed Nicols; x 80).

Specimen No. 130. Red non-porphyritic granite.

Macroscopic: The rock consists of an extremely coarse graphic intergrowth of quartz and felspar. No femic minerals are observed in the hand specimen.

Microscopic: Texture: Graphic intergrowth.

The rock is formed of a graphic intergrowth of quartz and orthoclase which shows some suggestion of microcline cross-hatching. It is considered that the one is forming from the other. One small crystal of ore, either haematite or magnetite, is present in the section.

Specimen No. 91. (Plate XXXIV). Red non-porphyritic granite.

Macroscopic: The rock consists of a delicate intergrowth of quartz and felspar.

Microscopic: The rock is much finer than No. 130 and consists of a graphic intergrowth of microcline and quartz. The microcline is perthitic and it appears that sodic material is replacing quartz along mutual boundaries.



Plate XXXIV. Red non-porphyritic granite.
The photograph shows a graphic intergrowth of microcline perthite (P) and quartz (Qz)
(Crossed Nicols; x 30).

Specimen No. 72 (Plates XXXV and XXXVI). Pegmatite.



Plate XXXV. Pegmatite (No. 72).
Perthitic microcline (P) surrounds corroded quartz grains in the slide. Myrmekite (Mk) is in turn replacing the microcline.
(Crossed Nicols; x 80).

Macroscopic: This rock is pink in colour and is non-graphic. It is made up of quartz and felspar.

Microscopic: Texture: Granitic.

The dominant mineral present is microcline. It is somewhat perthitic, and occasionally includes corroded quartz grains. Myrmekite is abundant. A little apatite and zircon are present in the rock.



Plate XXXVI. Pegmatite (No. 72).
Perthite (P) and myrmekite (Mk) occur together with groups and single crystals of zircon (Zr).
(Crossed Nicols; x 80).

Specimen No. 33. Pegmatite.

Macroscopic: This is a typical specimen of the pegmatites which are intruded near the ore horizon. It is grey and pink in colour. Quartz does not form an intergrowth with felspar, but appears as blebs within the latter mineral.

Microscopic: Texture: Granitic.

The rock is made up of cross-hatched microcline, which is rarely perthitic, with blebs of quartz which often appear to be in the process of replacement by the felspar.

CHAPTER VII.

PETROLOGY.

1. Rocks of the Damara System.

The probably origin of the sediments of the Damara System has been discussed under the heading "Geological History of the Damara Period". The rocks, however, have undergone extreme changes since deposition, and the causes, processes and results of their metamorphism will now be discussed.

The regional metamorphic effects may be divided, for convenience of description, into those directly dependent on directed shear or stress, those due to high temperature and accompanying high hydrostatic pressure, and those due to pneumatolysis. The fabric of the rock as represented on the macroscale by cleavage, gneissosity, lineation etc., and on the microscale by texture under the microscope, is directly related to the forces which affected the rocks. In general, the minerals formed are related to the chemical changes resulting from instability at the high temperatures and pressures, although their formation may be further influenced by directed stress. Superimposed on the normal metamorphic processes, further instability and accompanying change in mineralogy is brought about by the addition of water, chlorine, potassium etc., the source of which may in part be sought within the rocks themselves, but which may also be derived from lower in the crust, from granites or a granitic ichor.

Many of the rocks of the area fall into the category of migmatites, i.e. rocks into which granitic material was introduced during metamorphism, and examples of these will be discussed in detail.

(a) The Metamorphic Effects Due to Directed Stress or Shear.

The crystal growth of the metamorphic rocks has taken place in a medium which was mechanically anisotropic and thus in the rocks studied a certain directional element is noted. Residual structures have generally disappeared, but in some rocks those originating in a lower grade of metamorphism still persist, a typical example of this being certain garnets which are developed in the gneisses, and which have the shape of the pre-existing chlorite, even though a high grade of metamorphism has been reached (Plate XV). The rocks on the macro- and micro-scales exhibit a tendency for the growing crystals to develop parallelism along planes related to the shear directions thus giving rise to marked schistosity (Plate XXII). Where pronounced aggregation of particular constituent minerals into lenses or streaks takes place the rocks become foliated (Plates XX and XXI).

In most of the rocks types the schistosity and foliation is so obviously related to the shear stresses that macro features are a sufficient guide to the tectonic pattern and petrofabric analysis is of little aid to the field geologist, especially since outcrops are few and far between, and an extremely complex structural pattern is reflected throughout the area.

One enigmatic texture which must be noted is the decussate nature of the tremolite marble (Plate XXVI). It is probably that the fibrous mineral did not attain any preferred orientation because the yield strength of the surrounding limestone was so low that the forces were dissipated within this rock type and therefore did not exert their effect on the more rigid rock.

(b) The Effects of Regional Metamorphism on the Sedimentary Rocks.

In this section the metamorphism of the manganese

beds will not be discussed, as the description of these will form portion of the section on economic geology. The original rocks of the area included limestones, marls, shales, argillaceous sandstones and extremely pure quartzose sandstones. As a general rule, the rocks which were practically mono-mineralic in composition have merely recrystallized, examples being the quartzites and some pure marbles, whereas rocks such as calcareous shales have formed complex mineral suites. The modifying effects of pneumatolytic and metasomatic fluids are seen in the schists and granulites of the area, as well as in the development of scapolite in the calc-silicate rocks.

If the sedimentary equivalents of the metamorphic rocks are considered it appears that the changes that took place are as follows:-

(i) Quartzose sandstones gave rise to the extremely pure quartzites of the area. A white mica is observed in some of the members, whereas biotite is present in the slightly clayey group.

(ii) Argillaceous sandstones became converted into biotite-quartz granulites with various amounts of plagioclase, orthoclase and microcline. These rocks show the effects of metasomatic addition to be described later. Almandine (Plates XXXVII and XXXVIII) and sillimanite (Plate XXI) appear in some of the members. Where the sandstones were calcareous, hornblende and labradorite are present.

(iii) Shales, when metamorphosed, gave rise to biotite schists which resemble in mineralogy the derivites of the argillaceous sandstones except that biotite is more abundant.

(iv) Ferruginous sediments which included ferruginous shales, ferruginous marls and banded ironstones, became altered to biotite-haematite schists (Plate XXXIX),



Plate XXXVII. Biotite-almandine gneiss.
(Plane Polarized; x 30).

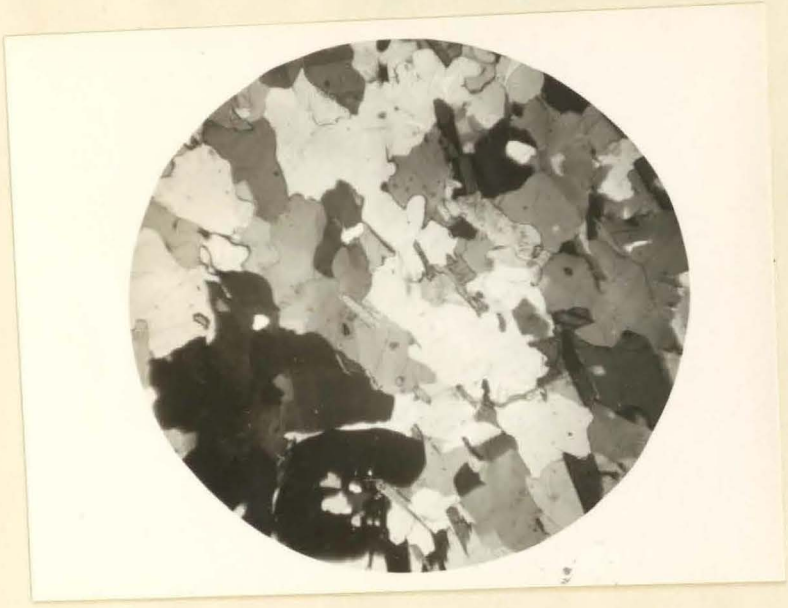


Plate XXXVIII. As Plate XXXVII.
(Crossed Nicols; x 30).

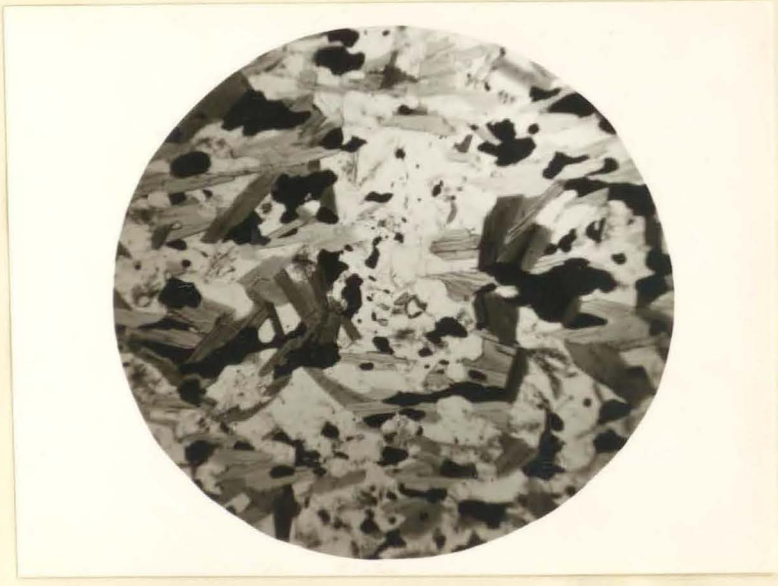


Plate XXXIX. Biotite - haematite schist.
Flakes of biotite (Bi) accompany haematite (He) in a groundmass of quartz and felspar.
(Plane Polarized; x 30).

hornblende-haematite schists (Plate XXII) and itabiritic schists. It is interesting to note that even though the rocks were subjected to at least the temperatures at which pegmatites were intruded, iron is not present as magnetite in the schists and quartzites of the area. Two factors no doubt played a part in the preferential formation of haematite. It is considered, firstly, that the platy form of the haematite is favoured under the mechanical shear conditions, and secondly, if, as will be shown later, the manganese beds were originally composed of manganese oxides the reactions which caused the metamorphism of these minerals must have released great amounts of oxygen. The oxidation of magnetite to haematite is fully described by Schmidt and Vermaas (1955). It is therefore concluded that the statement made by Harker (1950) viz. "In an advanced grade of metamorphism haematite gives place more or less completely to magnetite" is open to question, for in an oxidising atmosphere the differential thermal analysis curves of the magnetite-haematite reaction indicate this to be impossible.

(v) Marls gave rise to rocks containing hornblende and diopside as index minerals. Quartz and plagioclase are often present in these rocks (Plate XIV), while grossularite (Plates XV and XVI) and scapolite (Plates XVII and XVIII) are noted.

(vi) Pure limestones merely recrystallized to form pink, white and grey-blue marbles. Carbon is often present in the form of graphite. The presence of sulphurous gases trapped in these rocks will be discussed under metasomatism.

(vii) Pure magnesian limestones present a further problem. Harker notes that "with a lower pressure, dolomite dissociates, but only as regards its magnesian part"

$$CaMg(CO_3)_2 \longrightarrow CaCO_3 + MgO + CO_2$$

The resulting rocks, periclase-marbles (pencatites) and periclase-brucite marbles (predazzite; Plates XXVII and XXVIII) are found in the metamorphic assemblage of the area. It is obvious that pressures were extremely high and Harker (1950) again states "The pencatite type is not represented in regional metamorphism, pressure being too great to permit even so much dissociation of a carbonate in the absence of silica". It is therefore not certain why this anomalous rock type is present in the area and it must be concluded that its formation took place either at the onset or the decline of the metamorphic period, when the pressures were sufficiently low to permit dissociation.

(viii) Arenaceous limestones have given rise to wollastonite-idocrase marbles.

(ix) Arenaceous magnesian limestones formed tremolite marbles, but the stage at which tremolite is replaced by diopside and forsterite was not reached in the rocks studied.

It appears that except for the pencatite referred to above, all the metamorphic rocks of the area lie within the Amphibolite and Granulite facies as defined by Turner and Verhoogen (1951). The Amphibolite facies embraces the range of temperature and pressure for which the assemblage hornblende-plagioclase is stable. The highest temperatures of this facies must have been reached since members of the Sillimanite-Almandine subfacies are also represented, and true light-coloured "acid" granulites are present. The conditions, which were necessary for the rocks to reach this level of regional metamorphism, are found to have wide distribution in Pre-Cambrian gneisses and in deeper parts of the orogenetic mountain ranges throughout the world.

(c) The Effects of Metasomatism and Pneumatolic Processes.

Although the area is not ideal for the study of metasomatism, granitization and allied processes, certain

rocks of the area are of interest in these connections. It is uncertain where much of the added material has come from, but some of the rocks are so obviously not derived from metamorphic processes sensu stricto that these must be considered apart from the rest.

Many of the quartzo-felspathic rocks of the area are extremely potash rich, and the development of microcline and perthite porphyroblasts are a feature of these gneisses, granulites, and schists (Plates XIX, XX, XXIV and XXV). Cordierite and anthophillite, minerals which are generally noted in non-potassic rocks of the amphibolite facies, are absent from the assemblage. The great amounts of microcline and to a lesser extent orthoclase and perthite, developed in the schists, granulites and gneisses, together with the petrographic relationships of these minerals to others in the rock, leads to the conclusion that the original sediment was not so rich in potash. It is concluded that the large microcline porphyroblasts are at least in part due to the fixation of alkali by the excess alumina in the metamorphic derivatives of former shales. The addition of sodic material is not so widespread but the fact that sodic veins replace microcline and orthoclase indicates its mobility under the metamorphic conditions.

Scapolitization of the diopside-plagioclase granulites (Plates XVII and XVIII)is another feature of the rocks of the area. The possibility that all the necessary volatile components (CO_2, H_2O and SO_3) were present in the materials forming the rocks undergoing metamorphism is not denied; however, the abundance of apatite, and sphene in these rocks is typical of regional-pneumatolic-metamorphism in which phosphorus, sulphur, chlorine and titanium are added to the bulk composition of the rock.

One feature which is not compatible with a permeating granitic ichor moving as a liquid or gas through the rocks

must, however, be noted. If the graphitic marbles are crushed they emit a sulphurous smell, which is doubtless due to the release of gas which was trapped within the calcite grains. This feature is typical of limestones developed under stagnant conditions. In considering a moving front of fluid to explain the metasomatic effects, it seems strange that the sulphurous gases were not set free to join this front and move with it. Permeability of the rocks seems to be the only answer to this problem, and in fact it is noted that gneisses, schists, and granulites were very much more open to attack than the limestones of the area.

(i) Development of microcline porphyroblasts:-

The development of microcline porphyroblasts takes place in two ways. In the case of former pelitic sediments the rock develops a pseudo-cataclastic texture (Plates XIX and XX), the direction of which parallels the regional schistosity or gneissosity. Within the pseudo-cataclastic groundmass isolated microcline porphyroblasts grow (Plate XX). They are often longer in the direction of the foliation, than at right angles to it. Within the groundmass, sillimanite (Plate XXI) and garnet, both high temperature minerals may be developed, whereas on the periphery of the porphyroblasts myrmekitic intergrowths of quartz and sodic felspars are observed (Plate XIX). This myrmekite, which corresponds to the type 1 group as defined by Drescher-Kaden (1948), is due to the assimilation of groundmass material by the growing microcline porphyroblasts. At a later stage the porphyroblasts grow to the extent that they are only separated by a small film of apparently mylonitised quartz-felspar groundmass (Plate XIX). At this stage the rocks have probably reached the level of metamorphism embraced by the granulitic facies. The amount of biotite declines, and there is no doubt that the potash

from this mineral adds to the amount of microcline formed. The rocks now conform to the description given by Turner and Verhoogen (1951) viz. "qartzo-feldspathic garnet or pyroxene gneisses with little or no mica, in which quartz occurs in flattened lenticles or leaves oriented (by grain form) parallel to the foliation".

At this stage the microcline may become perthitic, and fine perthite lamellae develop in some of the grains. Superimposed on the fine exsolution features, coarse sodic veins, which often parallel the foliation of the groundmass, are developed within the porphyroblasts. The presence of myrmekitic intergrowths on the periphery of the grains is still marked (Plate XIX).

It is suggested from evidence of slides that the potassium required for the development of these large microcline or perthite porphyroblasts had an origin other than within the sediment itself and that the development of these porphyroblasts is due to metasomatic phenomena.

In the case of more arenaceous rocks the process of microclinization took a different form. The first stage was the simulataneous recrystallization of quartz, microcline and plagioclase, as shown by the mutual interlocking texture of the grain boundaries. The amount of microcline is observed to increase and coalescing grains become optically continuous, isolating quartz and biotite grains (Plates XXIV and XXV). It is interesting to note that the biotites do not break down rapidly to yield their potash to the microcline, but retain their crystal form, within the enveloping grains. Within these rock types reaction between potash felspar and plagioclase has resulted again in the development of myrmekite, the age of which can be deduced as later than the twinning in the plagioclase (Plate XXIII).

Close to the pegmatites intruded near the manganese

horizons augen gneisses are developed in the schists of the Itabirite Schist Zone. In these rocks both potassium and sodium has been introduced, as evidenced by perthitic felspars which form "augen" in the biotite-haematite schists of the Ann Mining Area.

(ii) Sodium metasomatism. As a general rule the addition of sodic felspar to the gneisses and granulites is not as widespread as the addition of potassium. It is obvious that sodic felspar replaces potash felspar in many of the slides studied; however, as a rule the amounts involved could easily be provided by the rocks undergoing metamorphism. In the case of one rock however, sodium metasomatism appears to have played an important part. The rock is considered to be a recrystallized arkose. The quartz grains, which are perfectly rounded, are set in a mass of perthitic and antiperthitic felspars. The potassic felspars are in the process of replacement by the sodic material (Plates XXIX and XXX). Sphene is present in abundance in the slide, and it is probable that it has formed from original ilmenite grains. Calcium either present in the original rock or introduced by impregnating solutions, could account for its formation. It is further worthy of note that the rock is intensely green in colour. Ramberg (1952) states that "the felspars are also extremely typical of rocks belonging to the granulite facies. Not only do they exhibit a dark greenish to brown or grayish-black colour, but also the particular perthitic structures are unshared by felspars from other facies". This statement agrees with what has been noted so far; however, Ramberg (1952) states further that "sphene, which is stable in all other normal facies does not occur in the granulite facies except in the lime-rich skarn rocks". It appears, therefore, that this is further proof that a mere recrystallization at temperatures and pressures embraced by the Granulite

facies is not sufficient to account for the formation of of this unusual rock type and that metasomatic agents must have been active to explain all its features.

In concluding the discussion on the felspars of these metamorphic rocks the views of H.H.Read on this phenomenon are worthy of quotation. In "Meditations on Granite" (1944) he states ".... whatever felspathization once meant, I maintain that it does not mean an impregnation with felspar derived from a magmatic source. In felspathization, material for the formation of felspar may be contributed by the country rock, and by the introduced solutions, magmatic or otherwise".

(iii) Scapolitization.

In some rocks of the area scapolite takes the place of plagioclase, whereas in others the two minerals are associated. Lime scapolites of the type found at Otjosondu are known to form in limestones during normal regional or contact metamorphism, the necessary volatile components (CO_2, H_2O, SO_3) being supplied by materials already present in these rocks. On the other hand, where an abundance of apatite and sphene is noted in the rocks, and such is the case in point, it is considered that a metasomatic origin is likely. Where widespread metasomatic scapolization remote from igneous intrusions (i.e. not skarn types) has been noted, the term "regional-pneumatolitic metamorphism" has been applied.

2. The Granites and Pegmatites of the Area.

There remains very little to report on the granites and pegmatites of the area except to compare and contrast the mineralogical compositions of the various groups with one another. These data have been presented in Table VI.

TABLE VI.

PETROLOGICAL VARIATIONS OF THE GRANITIC ROCKS.

	Gneiss-Granite	Red Porphyritic Granite	Non-porphyritic Granite	Pegmatites	Granitic gneiss associated with Pegmatites
Texture	Porphyritic	Porphyritic	Non-porphyritic sometimes graphic	Graphic and Pegmatitic	Augen
Dominant Felspar	Oligoclase Microcline	Orthoclase and Oligoclase	Microcline Perthite	Microcline	Microcline and Orthoclase
Dominant Femic Minerals	Biotite and occasionally hornblende	Biotite	Generally lacking	Generally lacking	Biotite haematite

PART II.

ECONOMIC GEOLOGY.

CHAPTER I.

DESCRIPTION OF THE MINING AREAS.

Probably the most important and interesting task of the mining geologist in the Otjosondu area is the elucidation of the structures of the ore bodies. These are considered to be in part lenticular, but as they lie on definite planes within the geological profile their interrelationship may be deduced in almost every case. As the stripping of overburden proceeds, it appears that many bodies, at first thought to be small isolated lenses are in fact linked by formerly unexposed portions. The effects of this are that mining is facilitated and the field's potential tonnage is increasing. This leads to the question as to whether all the ore-bodies will be connected in some way at depth. At the present stage of development no definite answer can be given; however, where gaps do exist between ore-bodies, the itabirite-quartzite contacts have been studied whereever possible, and it is often noted that reversal of plunge direction, or lensing out due to structural factors could explain the absence of ore on the present erosion plane, but in depth the individual bodies may well be linked. On the other hand, a few bodies have been reported to stop down-dip, but it is extremely difficult to determine whether this is again due to lensing out of the manganese beds during folding, or whether primary depositional features are the cause.

In the first descriptions of the area the number of ore-horizons listed varied from one to several. A published description by Jounert (1952) suggested that two horizons existed. The present survey has confirmed that these two

horizons exist in the sequence as described; however, a third is developed within the Itabirite Schist Zone bringing the total to three, these being termed the Lower, Middle and Upper Ore Horizons. The Lower Horizon has for its footwall the Lower Quartzite as developed at Otjosondu Kop, and for its hanging wall the Itabirite Schist Zone. The Middle Ore Horizon is developed entirely within the Itabiritic Schists and has schist above and below. The Upper Ore Horizon lies between the Itabirite Schist Zone and the Upper Quartzite. Above the Upper and below the Lower Ore Horizons a thin schist parting may exist between ore and quartzite, and within any one of the ore horizons rare schist lenses may be noted.

In the description of the mining areas special note of the structure is made, for it is considered that as mining proceeds this factor will become more and more important. Structural details for each mining area are those which could be obtained from observations made on outcrops, and in workings at the time of survey. New data will be forthcoming as mining proceeds, but the basic pattern has been established.

Fairly large scale maps of portions of the Ann, Cheri, Dale and Furman Mining Areas are appended, as these are considered to have the greatest potential within the field. The symbols used for dips, strikes, plunges etc. are the same as those of the regional map.

1. Ann Mining Area.

Before a detailed description of the Ann Mining Area is given, the broader general geology of the area around the Otjosondu Kop will be noted. The Otjosondu Kop itself is formed of a doubly plunging anticlinal quartzite mass. Towards the east plunges are noted to be eastward, whereas to the west of the Kop westerly, northerly, and northwesterly lineation has been observed. To the north

of the Kop there is a small doubly plunging quartzite hill. The most important bodies are developed to the north of the Kop (Ann Mining Area), but the Itabiritic zone almost surrounds the quartzite eminence completely and thus smaller bodies are found to the south (Otjosondu South) and west (Jeppe Mining Area) of the Kop.

The bodies of the Ann Mining Area will be described from West to East.

(a) Ann 16 (Otjosondu West).

Both the Upper and Lower Ore Horizons are present in the Ann 16 Area, the ore bodies being developed within a syntaxial zone where the normal east-west strike of the beds is abruptly changed to a north-south strike. Drag folds still retain the east-west orientation even where the general strike is north-south, and lineation is generally developed in an east-west direction where drag is intense. On the straighter limbs of the folds the lineation is, however, almost north-south with dips towards the north. To the south of the quartzite knoll, which forms a synclinal core, the southern ore body, which is a member of the Lower Ore Horizon, is absent or as yet uncovered. If this horizon is found, by drilling, to be indeed absent, then without doubt the manganese ore ruptured in this zone of tension and its disappearance is purely due to structural cause.

Pegmatitic material has been intruded into the itabirite schists, and finds its greatest development where small drag folds have offered zones of easy ingress.

Towards the north, the Itabiritic Schist Zone will no doubt coalesce with that noted at Jeppe.

(b) Ann 13.

In this working area only the Upper Ore Horizon is developed. From the Ann 16 workings its outcrop strikes north, noses around a quartzite knoll, which forms

the core of a northward plunging syncline, and then forms a tightly closed anticline. The direction of lineation in the workings is noted to be at high angles to the north-east.

A vertical pit has been sunk to a depth of 45ft. in one of the workings, and this permits a close inspection of an almost vertically plunging drag fold. The hanging wall of the body is quartzite but the footwall is only represented by a thin band of selvage material on the southern side of the pit. The minor flexure has been almost completely closed and the major portion of the schist has been squeezed out between the two limbs of ore. This demonstrates that the thickening of ore bodies may often be accounted for not by conditions active during the depositional period, but by closed folding and drag.

To the south of the quartzite knoll small workings follow the outcrop of ore and the curve of the synclinal nose can easily be seen.

The schists have been intruded by pegmatitic material but this does not appear to have adversely affected the grade of ore.

(c) Ann 7.

The Lower Ore Horizon reappears towards the east in the Ann 7 workings. The structure is straightforward, the ore being developed on the southern limb of a major fold, the axis of which strikes almost east-west. To the north the body has a schist contact, whereas to the south quartzite and pegmatite are noted. The more or less straight east-west strike is maintained by this horizon until the Ann 3 Workings are approached.

(d) Ann 3.

The ore body, which represents the Lower Ore Horizon, is situated on an eastward plunging anticline. The outcrop runs parallel to a quartzite knoll to the Ann 7

workings; however, on the east it forms a closed syncline, and the structure is complicated by the intrusion of pegmatite. The body dips at high angles to the north and plunges about 30°E. Instead of the normal schist hanging, the body has been intruded on its northern contact by pegmatite which has, however, not adversely affected the grade of ore, the tenor being high; the main ore mineral is braunite.

A sharp nose is developed near the present motor road, and the body continues on the southern side of the quartzite knoll. A few workings are situated on this side of the hill and dips are noted once again to be at high angles towards the north.

(e) Ann 1.

The Upper Ore Horizon, after being folded into the closed anticline at Ann 13, runs parallel with the Ann 7 body until it reaches the Ann 1 workings. This mining area consists of a very high grade body, which at the time of mapping was being worked, and to the south a lower grade body which is exposed in crosscuts. The northern body (Plate XL), which is separated from the other



Plate XL. View of the Ann 1 working.
The photograph shows the broad manganese body plunging towards the left under the quartzite (stippled). On the right the footwall of the quarry is formed by schist and pegmatite.

by itabirite schists and pegmatite, belongs to the Upper Ore Horizon, whereas the southern body, which has both schist and pegmatite on hanging and footwalls, represents the Middle Ore Horizon. "Cross folding" has caused the bodies to be thrown into a North Eastward plunging syncline. Lineation, in the form of small folds on the bedding of the quartzites, plunges 65°NE on the working face. On the quartzite to the north-east of the body, however, lineation is observed to plunge towards the northwest. Similar variations in plunge direction of this type of lineation have been observed wherever it is associated with "cross-folded" structures. The lineation is, in these cases, not parallel to the major fold structure, but is related to the plunge of the minor fold axes.

In the high grade body hollandite is plentiful and it may be distinguished in the hand specimen by its needle-like form and its high lustre. It is accompanied by braunite which is relatively fine grained.

(f) Ann 2.

The ore bodies, after being deformed into the north-eastward plunging syncline observed at Ann 1, are folded in a gentle north-eastward plunging anticline and a further syncline before being caught up into a tight north-westward plunging anticline at the Ann 2 Workings. Two large quarries are developed on the Upper Ore Horizon whereas the Middle Ore Horizon is exposed in a small quarry to the south.

(g) Ann 15 (Incline).

The Upper Ore Horizon continues to strike ESE towards the No. 15 incline shaft. Except for minor crenulations the body parallels the regional fold direction has dips of about 60° towards the north and shows westward plunge as evidenced by lineation developed in the quartzites.

The Middle Ore Horizon is not developed in this area.

An inclined winze has been sunk on ore.

(h) Ann 8, 9, and 10.

The body exposed in these workings is developed on the southern limb of a syncline. Its footwall is formed of quartzite and its hanging schist and pegmatite. It is the equivalent of the body mined at Ann 3, and therefore belongs to the Lower Ore Horizon. The plunge of lineation within the quartzites is 35°W.

(i) Ann 5 and 6.

This ore-body is not observably continuous in outcrop, being followed on strike by a series of disjointed workings. As these are developed, however, the continuity of the ore is being proved. Structurally it is relatively simple, but some sharp folds are noted which, as opposed to their counterparts at Ann 1, have plunges parallel to the major fold axes. The body has a quartzite hanging wall and a schist footwall (Plate XLI) and thus is a member of the Upper Ore Horizon, its continuation being noted at the Ann 15 Incline workings.



Plate XLI. View of the Ann 6 Working.
The photograph shows the ore body dipping under the Upper Quartzite (stippled). The footwall is schist.

(j) Ann 11.

This ore body is the continuation of the body worked at Ann 5, its displacement towards the north being caused by a sharp westward plunging drag fold, the axis of which practically parallels the regional fold direction.

2. Jeppe Mining Area.

After being folded into a series of anticlines and synclines in the Ann 16 area the Itabirite Schist Zone and the accompanying ore horizons strike northwards where they are overlain by deep sand. On aerial photographs it is easily noted that these horizons form a nose and swing back towards the Otjosondu Kop. This structure is a northward plunging anticline. As the ore horizons once again approach the Kop two bodies outcrop at the Jeppe Mining Area. They are, as yet not opened up, but are considered to be the representatives of the Upper and Lower Ore Horizons, the Lower body showing in outcrop a much better development than the Upper. The Lower body strikes east-west in the west, but then swings northwards towards the anticlinal nose mentioned above.

3. Otjosondu West Mining Area.

On the western slopes of the Otjosondu Kop a body was prospected by a former company working in the area. As its grade at surface is low it has not been developed. It is considered to be an extention of the Lower Ore Horizon as developed at the Jeppe Workings. Once again in this area the strike of the body is north-south, but minor folds cause rather abrupt changes in the outcrop pattern. The angle of dip varies from 40° to 80° W. The body is intruded by pegmatite.

4. Otjosondu South Area.

To the south of Otjosondu Kop a small ore body of relatively low grade is developed. On the north of the body

pegmatite is intruded into schist whereas the southern contact is quartzite. The body thus represents the Upper Ore Horizon.

It appears that to the east of the Otjosondu South Area the ore horizons must form a further nose, and thus there exists a distinct possibility of finding ore to the south of the Otjosondu South Area, to the West of the Otjosondu West and Jeppe Areas, and to north and west of the Ann 16 Workings.

5. Bodies Between the Ann and Cheri Areas.

These bodies, which have not yet been given a name are ill-developed and are generally of low tenor. They are cut off from the Ann and Cheri workings by faults and are situated on a series of drag folds whose axes strike E.N.E. Dips between 70 and 45° N have been recorded.

6. Cheri Mining Area.
(Ebenezer, Oparakane and Houmoed Farms).

The ore bodies of this area are developed on a series of anticlines and synclines which themselves form a basin structure, the hub being near 1 Wat survey beacon. Tracing the ore horizon from the direction of Otjosondu it is found that the first ore body of the Area is developed to the West of Cheri 2 workings. It has as yet not been opened up. The schists then trend north-east and two further low grade bodies are developed on their strike. Unlike the body to the West of the Cheri 2 Workings, which is a member of the Lower Ore Horizon, these belong to the Upper Ore Horizon. To the north of the Cheri 3 workings a nose is developed and the schists trend eastwards to the Cheri 2 area.

(a) Cheri 2.

The ore body is developed on the northern and southern limbs of a synclinal structure. Some normal dips i.e. 25 to 65°S were observed on the northern limb but they soon become vertical, and then are steeply overturned viz. 70°N.

(b) Cheri 6B.

This body is situated on an anticlinal nose, the ore body swinging north westward to form the synclinal structure of the Cheri 2 area, and south westward towards a second synclinal structure on which the Cheri 6A and Cheri 1 workings are developed.

(c) Cheri 6A.

The ore body is developed on the northern limb of a synclinal structure, its continuation being worked at Cheri 6A to the north east and Cheri 1 on the southern limb of the syncline.

(d) Cheri 1.

This body is situated on the southern limb of a synclinal structure. This ore, together with that mined at Cheri 6A, Cheri 6B, and Cheri 2, belongs to the Upper Ore Horizon. The lineation on the quartzites is seen to plunge at about 30°E. The ore is of good tenor.

To the west of Cheri 1 workings the body is seen to form a nose, which trends north-south towards the lower grade bodies to the south.

(e) Ores to the South of the Cheri 1 Workings.

Both the Upper and Lower Ore Horizons are represented in the ores developed to the south of the Cheri 1 Workings; however, little ore of high grade appears to to be forthcoming from these bodies. To the east the general trend of the itabirite schists is towards the north where they once again are exposed in the Cheri 5 Workings.

(f) Cheri 5.

Just to the north-east of Cheri 6A the Cheri 5 workings have been developed on ores of both Upper and Lower Horizons. The structure is a series of anticlines and synclines of small dimension, but it is worthy of note that there appears to be a definite similarity of structure to the east and west of an axis which runs almost

north south between the Cheri 6 B and Cheri 5 workings.

The Ore horizons once again appear to assume a more or less straight trend towards Cheri 3.

(g) Cheri 3.

The area around Cheri 3 is very interesting in that not only solid manganese ore is developed but an important deposit of high grade detrital ore is being worked. Considering firstly the detrital deposit, it is noted that similar deposits have been described by Fermor (1909) from India. In the case of the Otjosondu Area the ore consists of particles ranging from the size of peas to the size of a man's fist. They range in roundness from practically perfect spheres through ovoids to muffin shapes, but angular fragments are conspicuous by their absence. They may be cemented by either a clayey sand or secondary limestone, or occur uncemented in the quartzose sands. The depth to which they persist is as much as four feet. The zone at present being worked lies to the north of Cheri 3 i.e. overlying the Itabirite Schists.

Several facts lead to the conclusion that the ore is present in a former channel, or river bed. The degree of rounding cannot be accounted for by the short journey from the nearby ore body especially when the low gradient is considered. Furthermore the water table in this area is very high. The bottom of the Cheri 3 workings is filled with water although they are only about 30 ft. deep. This is in marked contrast with the considerably deeper water table of the rest of the area.

The systematic exploitation of this detrital deposit should be stressed, for production is extremely cheap, the ore, due to leaching, is generally higher in tenor than the parent material, and the working of this type of deposit can often pay for the development of ore bodies requiring more costly mining procedures. One of the greatest handicaps

in the exploitation of this ore, however, is that loading is carried out by means of forks. Any ore not large enough in size to be held between the teeth of these tools is discarded; furthermore, only a certain amount of shipped ore may be smaller than specified sizes without incurring penalties.

The Cheri 3 body itself is one which has reportedly vanished both on strike and dip. The lower portion of the workings are, at the present time, flooded with water, and as they are being filled in during the exploitation of the detrital deposits, a detailed section throughout the rocks bounding the body is worth recording. To the south the footwall is quartzite containing flakes of haematite. This mineral increases in quantity towards the ore body and a thin (1 ft.) pure haematite band is noted. Further towards the body a 6 inch thick band of itabirite carrying biotite is noted. The latter mineral increases in amount and 4 inches of biotite-schist is developed immediately in contact with the ore. On the hanging-wall side of the bod a hornblende-haematite-biotite schist is developed. The body strikes E.S.E. and dips at about 65° N.

Within the schists, a second ore body was developed. It has now been removed by mining; however from the fact that it has schists on both hanging and footwalls it is concluded that it is a member of the Middle Ore Horizon. Throughout the length of development of ore in this zone, the Lower Ore Horizon body showed an increase in grade, whereas to the east where the body in the schist disappears the grade decreases somewhat.

As this body was reported to have disappeared in depth it should be noted that during diamond drilling operations a continuation of the ore was found both in depth and on strike. The drilling, however, did not re-locate a body of sufficient size to encourage continuation of the working.

Thus an economic, not a geological factor caused the "bottoming" of the body.

(h) Cheri 3 B.

In the Cheri 3B area both the Upper and Lower Ore Horizons are developed and two parallel series of workings exist trending towards the Dale Working Area. As a general rule it is noted that most of the ores of the Cheri Area have been developed on the Lower Ore Horizon; however, at Cheri 3B both horizons are well developed.

7. Dale Mining Area. (Ebenezer)

The structure of the ore bodies in the Dale Mining Area is extremely complex. As in the case of the Jeppe and Ann 16 Areas the bodies are situated on a zone of folding where the trend of the folds swings from east-west to north-south. North-south strikes on ore bodies are, however, rare and the east-west trend is still important in that the ore bodies lie on drag folds having an eastward plunge. This is in contradistinction to the Eric bodies, which show lineation closely approaching the north-south outcrop pattern even though the ores strike almost east-west.

The result of the drag folding is to increase the outcrop area of the manganese horizons, and thus several large, high grade lenses are worked in the area.

(a) Dale 4 B.

From Cheri 3 B the Itabiritic Zone strikes towards the south-east and at Dale 4B ore bodies correlated with the Lower Ore Horizon are involved in a series of folds with axes oriented in a north-westerly direction.

(b) Dale 6 C.

The Dale 6 C workings are being developed on a limb of the fold structure observed at Dale 4 B. The strike of the bodies is towards the south-east.

(c) Dale 4 A.

At Dale 4 A, all evidence of the north-west

orientation of fold axes disappears and the strike of the body is almost east-west. The ores of the Dale 4B, 6C, and 4A areas appear to be somewhat inferior in grade when compared with some of the other Dale Areas.

(d) Dale 1 A.

The Lower Ore Horizon is next developed in the Dale 1 A workings. The bodies strike east-west and lineation dips towards the east. Close to the Lower Ore Horizon a body having schist on hanging and footwalls is developed and thus is correlated with the Middle Ore Horizon. Some very high grade ores were developed in the Dale 1A area.

(e) Dale 1.

The Dale 1 workings are situated on the nose of the large synclinal structure of the Dale Area. Strikes approach the regional north-south orientation of the outcrop pattern, and pegmatite has been intruded into the tension zone. The strike of the body in the most southerly extentions of these workings shows again the east-west orientation and trends towards the Dale 3 workings. On the noses of the series of drag folds, which are superimposed on the major synclinal nose, the average pitch close to the surface is 50°E, and this may thus be taken to be the pitch of the major fold.

(f) Dale 3.

This working area includes the last outcrop of the Lower Ore Horizon in the Dale section. Dale 3 working, which produced some very rich ore, is situated on a minor structure which again shows the effect of the north-south trend superimposed on the east-west one. Lineation dips at 55°E, but the body often shows north-south strikes.

(g) Dale 5 B.

The Upper Ore Horizon makes its first appearance in the Dale Area at this working. Strikes are

towards the east, and dips at high angles towards the north. Apart from minor crenulations the body is straightforward as regards structure, being situated on the straight portion of the northern limb of the Dale syncline.

(h) Dale 5 A.

This body owes its separate entity from Dale 5 B to an extremely sharp fold, which may have developed into a thust plane. It appears that Dale 5 A was originally a continuation of Dale 5 B, but during the folding it was either folded or sheared from its former position to present an abnormal duplication of the ore body, as it appears to have quartzite on both foot and hanging walls.

(i) Dale 5 C.

This body is the continuation of that developed at Dale 5 B.

(j) Dale 5 D.

The Dale 5 B body is worked intermittently along strike at 5B, 5C, and 5D. Where the body is absent some small pits at surface indicate the complete absence of manganese material between the schist and quartzite at surface. This must be due to depositional features for it is doubtful whether flowage of the manganiferous material would entirely remove any deposited manganese, especially from the straight limbs of the folds.

(k) Dale 7 B.

The Upper Ore Horizon may be followed eastward to the Dale 7 B working which lies on the southern limb of the Dale syncline.

(l) Dale 7 A.

This working marks the eastward extremity of the Upper Ore Horizon bodies in the Dale Area. To the east of the body a sharp nose must be developed in the schists and the trend of these rocks is once again towards Dale 2 and thence southward to the Eric Workings.

(m) Dale 2.

This body lies near an anticline nose which plunges towards the east. Minor bodies are developed on the southern limb of the anticline. The ore horizons now strike southward towards the Eric Workings.

8. Eric Mining Area. (Ebenezer).

The bodies of the Eric Area (Plate XLII) are representatives of the Lower Ore Horizon. The northern



Plate XLII. View of the Eric Working Area.
The one figure is standing on the ore horizon which plunges beneath quartzite. Lineation in the (a) plane is developed on the quartzite. The other figure stands on schists.

contact of the body is quartzite, which shows interesting linear features, and the southern contact is schist. The main body strikes east-west, where exposed, but lineation in the quartzites dips towards the north. The lineation is developed on small folds which are about 2 to 3 ft. in section as well as on small ruffle lineation of less than $\frac{1}{2}$ inch in section. The fact that the linear element is at right angles to the strike could not at first be explained; however, as this body once again lies within the zone where the east-west folds are strongly influenced by forces which acted north-south, it is recognized that the lineation is related to the latter forces rather than to the regional

east-west ones.

It is considered that the Itabirite Schist Zone joins up with the Dale workings towards the north, whereas towards the west it is present in the Cathy; Lucy and Hettie bodies.

9. Cathy, Lucy and Hettie Area. (Otjosondu).

From the Eric Working Area the regional strike is once again towards the east and three small workings are scattered along the strike of the Itabirite Zone. Two of the bodies strike east-west, whereas the strike of the Hettie body is north south. The former two are as yet not developed; the latter, however, is being worked at the present time. It is of excellent grade and one of the few bodies of the area which shows definite evidence of supergene enrichment. It is interesting to note that whereas in general the ore horizons, when well developed, form slight ridges, the Hettie body is situated in a flat area where groundwater has no doubt been more active in leaching the ore. The Cathy and Lucy bodies are considered to be representatives of the Lower Ore Horizon, whereas the Hettie body is correlated with the Upper Ore Horizon.

10. Ore near the Omantumba-Eendrag Boundary.

Two small outcrops of ore are developed near the Omantumba-Eendrag farm boundary. They are isolated from the larger outcrops of the area and are of low grade. Probably both the Upper and Lower Ore Horizons are represented by the two small outcrops.

11. Furman Mining Area (Labusrus).

Apart from the Ann Mining Area, this section of the Otjosondu field has probably the greatest potential. It may be divided into five main areasof production formerly known as Labusrus South East, Labusrus South, Labusrus Central, which is shown on the map, Labusrus Central North and Labusrus North. The ore lies once again on the flanks

and noses of a series of anticlines and synclines whose axes generally plunge towards the West. In many of the workings the ores are displaced by north-south faults of small throw. The significance of these is not always apparent in the general structural pattern.

(a) Furman 8.

Once again following the ore horizon from the direction of Otjosondu the first section met is Furman 8. It was formerly known as Labusrus South East. Exposures in this area were unfortunately limited to a few disjointed outcrops of ore and quartzite, and thus the structure could not be fully determined. It appears, however, that the ore represents both the Upper and Lower Horizons.

(b) Furman 1 A.

Furman 1A together with Furman 1 and Furman 11 comprise the area known as Labusrus South. Furman 1A is a working developed on a synclinal nose. The low dips have had the effect of widening the outcrop and giving an erroneous impression of the thickness of ore. The ore body is a member of the Lower Ore Horizon.

(c) Furman 1.

Both the Lower and Middle Ore Horizons are represented in these workings. The ore lies on the southern limb of a westward plunging anticline. Two parallel east-west striking bodies, separated by itabirite and pegmatite, are developed. The northern contact of the first body is quartzite, whereas both contacts of the southern body are schist, which shows lineation plunging at 50°W. This area closely resembles the Ann 3 area in that the Lower Ore Horizon is high in grade along the length of the development of the Middle Ore Horizon, whereas to the east and west thereof the grade appears to decline. To the west the bodies are displaced by a small dip-fault.

(d) Furman 11.

In the Furman 11 working the Lower Ore Horizon is developed on the nose of a westward plunging anticline. From here the Itabirite Schist Zone trends eastward and northward towards the Labusrus Central Area.

(e) Furman 10.

The Labusrus Central Area is sub-divided into the Furman 10, 9, 2, 3, 4, 5 and 6 sections. The Furman 10 section represents the south-westward extremity of the ores of this area. Both the Upper and Middle Ore Horizons are represented in the workings. The ores are developed on the southern limb of a westward plunging syncline. The bodies are cut off to the east by a dip fault of small throw.

(f) Furman 9.

The bodies developed in the Furman 9 workings are the continuation of those worked at Furman 10. They also lie on the southern limb of the syncline. At the present time little development is taking place here as the higher grade ores to the north are attracting most attention. To the east the bodies are displaced by a second small fault.

(g) Furman 2.

Furman 2 working is developed on the nose of the westward plunging syncline. Once again both the Upper and Middle Ore Horizons are present, and the Ore is of good tenor. The lineation on the quartzites is noted to be 30°W.

(h) Furman 3.

The Furman 3 area has supplied a large tonnage of high grade ore and is at present being developed by underground mining methods. The Upper and Middle Ore Horizons are both present in the area, and owing to the fact that the workings are situated close to a nose, the

minor drag folds, which in the normal course of events, would not be exposed, are in this case laid bare. These digitations form more or less parallel bands of ore on surface and may be up to four in number. On these the Furman 3A and 3C inclined shafts have been developed, and these are at present following the ore along strike. Between the 3A and 3C shafts the ores are displaced by the same small dip fault which divides the Furman 9 from the Furman 2 workings.

Dips on this northern limb are between 50 and 60°N; lineation on the quartzites averages 35°W.

(i) Furman 4.

Along strike the ore bodies vanish in outcrop between the Furman 3C and Furman 4 workings. It is as yet uncertain whether non-deposition or structural factors cause this, and drilling should be undertaken in this section. Furman 4 opencast quarry has produced ore of good grade from both the Upper and Middle Ore zones. A small dip fault may be observed in the quarry. The plunge on the quartzite and schists increases in the workings from 35° to 50° W, but to the west of the Furman 4 shaft reversal of plunge direction must take place to account for the distribution of ore horizons. No reversed lineation was measured, however, but in the case of the Furman 5 shaft corrections had to be made in the sinking program as the development was projected to be on ore throughout, whereas due to this reversal of plunge the ore cut obliquely through the shaft section. To the west of the Furman 5 area the normal plunge direction i.e. towards the West is once against maintained.

(j) Furman 5.

A shaft is being sunk at the present time in the Furman 5 area.

(k) Furman 6.

After forming a nose the ore of the Upper Horizon is once again developed in the Furman 6 area. (Plate XLIII). It now lies on the northern limb of an anticlinal structure, and may be traced along strike to opposite the Furman 4 area. Here, too, a long body represents the Lower Ore Horizon, but in the absence of the Middle Ore Horizon these ores are generally lower in tenor than other ores of the area. To the north of the Furman 3 workings an anticlinal nose carries some ore which may be correlated with the Lower Ore Horizon.



Plate XLIII. Open Cast Workings at Furman 6.

(l) Furman 7.

The Furman 7 workings at Labusrus Central North are developed on a body of the Lower Ore Horizon. Plunge direction is noted to be towards the West. The ores of this body are of good grade. Between the Furman 6 and Furman 7 workings a few small bodies have been opened up in pits but these are as a rule of low grade, containing Jacobsite as their chief ore mineral.

(m) Furman 12. (Labusrus North).

The workings are developed on bodies of both

the Upper and Lower Ore Horizons, which lie on the northern limb of an anticlinal structure. The Upper Quartzite appears to have thinned appreciably in this area as marble outcrops are noted very close to the northern contact of the Ore. The Itabirite Schist Zone also appears to be less thick in the area, and this gave rise to the incorrect estimate of the thickness of the ore, for it appeared at first that the two bodies were in reality one. This working area, formerly known as Labusrus North, promises large tonnages, but as a rule the ores are rather jacobsite-rich.

12. Ore Bodies of the Ongorussengo, Weltevrede and Oparakane Areas.

The ores which occur on these three farms, may be described together as they are very similar in grade, structure and importance. The mining area on Ongorussengo exposed a few ore bodies on the same strike as the Furman 6 workings. Grade proved to be rather low. The Weltevrede bodies are developed on the northern limb of a major synclinal structure. The core of this syncline is formed of marbles. These bodies are also of low grade. Similarly the bodies of Oparakane, developed on the anticlinal nose, are of low grade and unimportant when compared with the abundance of higher grade lenses.

13. Bosrand Mining Area.

The important Bosrand bodies are situated on the nose of an anticlinal structure which plunges towards the west. Both Upper and Lower Ore Horizons are represented, and due to the low dips many of the ore bodies appear to be much thicker than they in reality are. Jacobsitic ores are mixed in confusing array with higher grade braunitic types. (Plate XLIV)· Relict banding, emphasized by garnet-jacobsite layers, are a feature of certain parts of the ore bodies. Much work will, no doubt, be necessary in the future to decipher the problems of ore grade variations in

these bodies.



Plate XLIV. Sorting of ore on Bosrand.
The ore of the Bosrand bodies is hand sorted by non-European labour and stacked in various grades.

14. Ore bodies of the Uitkomst and Okamatangara Areas.

The ores which are developed on these farms are very similar in nature to those described in Section 12. They are generally low in grade, the chief minerals being jacobsite and garnet. Little information is available as to the structures or possible improvement of grade in depth. It appears that where small, scattered and narrow bodies are developed the ore is low in grade, whereas where continuous thick lenses, such as those of the Ann, Furman, Cheri, and Dale Areas, are present, ore of higher grade may be expected.

CHAPTER II.

ORE STUDY AND MINERALOGY.

The manganese ores of Otjosondu were first described by J.E. de Villiers (1951). The ore minerals and the textures thereof are almost identical to the primary ores associated with the Gondite series as described by Fermor (1909) from India.

Probably the most important technique for the identification of manganese minerals is X-ray diffraction. The apparatus used in this study is a "Norelco" X-ray Diffractometer, which consists of three parts viz: a diffraction unit, a high-angle precision Geiger-counter goniometer and an electronic circuit rack with automatic 10 inch strip-chart recorder. Beam-reflection maxima, the diffracted rays at the Bragg angle θ, are automatically recorded as peaks by the Brown Elecktronik strip chart-recorder, and the "d" values together with line intensities thus obtained are used to identify the minerals.

As a general rule only manganese-filtered iron radiation is considered suitable for the study of manganese minerals; however, as an iron tube was not available the study was conducted using nickel-filtered copper radiation, which, although background was fairly high, permitted identification. Minerals containing small amounts of manganese were found to give almost the same amount of background, but it is important to note that all Bragg angle values are for this type of radiation, and the line intensities were calculated from the relative heights of the peaks, the highest of these being taken as 100. The actual "d" values remain the same for any type of radiation.

The equipment used for differential thermal analysis studies consists of a vertical Kanthal wound furnace; a Micromax program controller from which a substantially

linear rate of temperature rise of between 2°C per minute to 30°C per minute from room temperature to 1100°C, may be obtained; a phase-sensitive, rectifier type interupter-amplifier and a Speedomax Recorder. The specimen holder is a two-holedcylindrical nickel block. For temperature measurements 28-gauge chromel-alumel thermocouples were used, whereas the differential thermocouples consisted of 0.3 m.m. platinum/platinum 10% rhodium wire. Heating rate was 15°C per minute and the chart speed was 6 inches per hour for all specimens.

1. Ore Minerals.

The following minerals form the ores of the Otjosondu field:-

Braunite	-	$3(Mn\ Fe)_2O_3 . MnSiO_3$.
Jacobsite	-	$(Fe,Mn)_3O_4$.
Hausmannite	-	Mn_3O_4.
Vredenburgite	-	$(Mn\ Fe)_3O_4$.
Bixbyite	-	Mn_2O_3.
Hollandite	-	$Ba\ (Mn\ Fe)_8O_{16}$.
Pyrolusite	-	MnO_2.
Psilomelane	-	$Ba\ Mn_9O_{18}.2H_2O$.
Chalcophanite	-	$(Mn\ Zn)O.2MnO_2.2H_2O$.

A further mineral which is not in reality an ore mineral, but falls into this category rather than into the series of gangue minerals is:

Haematite - Fe_2O_3.

Most of the specimens examined, consist of either jacobsite and vredenburgite, or braunite, or a mixture of these minerals.

As a general rule, the braunitic ores are concentrated in the thicker bodies, whereas to the north east, where the bodies are often small, the ores are richer in jacobsite. The ores, as will be described later, vary from very fine types to coarse grained varieties, but, almost without

exception, they are crystalline. The occasional secondary pyrolusite and psilomelane types are, however, not crystalline, and indefinite x-ray patterns are obtained from these minerals.

Each of the above minerals will now be discussed but the textural relationships of the ores will be described in a separate section.

(a) Braunite $3(Mn\ Fe)_2O_3.MnSiO_3$.

This is the most important manganese mineral of the area. As a rule it is accompanied by jacobsite and this gives intermediate grades of ore; however, when found alone or with little admixed material the braunitic ores carry over 50% Mn. Two ages of braunite have been recognized in the ores, the first being due to metamorphic effects and the second due to pegmatitic agencies. The metamorphic braunites may be subdivided again into several groups dependent on the grain size and the accompanying minerals.

(1) Coarse grained braunite with a bright submetallic lustre and prominent cleavages, crystals often being over ½ inch in length and closely associated with pegmatitic braunite (Plate XLV).



Plate XLV. Coarse-grained braunitic ore - Labusrus (HR 165). Coarse-grained braunitic ore displaying a bright sub-metallic lustre.

(2) Medium grained braunite which also possesses a fairly bright sub-metallic lustre but which is distinguished from the first group by the general absence of cleavage and lesser grain size (Plate XLVI).



Plate XLVI. Medium grained braunitic ore - Bosrand (HR 106) This ore shows a reduced grain size when compared with that shown in Plate XLV. The lustre of the braunite is bright sub-metallic.

(3) Fine grained braunite which shows a dull sub-metallic lustre due to a further decrease in grain size (Plate XLVII).



Plate XLVII. Fine-grained braunitic ore - Labusrus. Note the fine grained texture, and steel grey colour. The lustre of such specimens is dull sub-metallic.

(4) Braunite-hollandite ore, which is strikingly different from the other types due to the distinct parallel orientation of the hollandite blades (Plate XLVIII).



Plate XLVIII. Braunite-hollandite ore - Otjosondu (HR 111 (a) & (b). The banded nature of the ore is well shown by the bright metallic lustre of the hollandite blades.

(5) Secondary porous braunitic ores which either display a dull sub-metallic lustre, or are completely earthy in appearance. These ores are developed where the jacobsitic material is altered, and the braunite remains as crystals within pyrolusite and psilomelane (Plate XLIX).



Plate XLIX. Porous braunitic ore - Otjosondu.
The ore has been altered to a porous mixture of pyrolisite, psilomelane and braunite. The bright metallic crystals are unaltered braunite, whereas the dull earthly material is a mixture of the two peroxides.

The braunite found within the pegmatites occurs as single well-developed crystals, often over ½ inch in length. They have their counterparts in haematite crystals, also formed by pegmatitic action and which may grow to 6 inches in length.

Various ore minerals were separated from ores collected during the survey by means of a Franz Isodynamic Separator by G. Groeneveld of the South African Geological Survey and certain of the mineral fractions were assayed at The Division of Chemical Services, Pretoria. Four assays of braunite were obtained and these are listed in Table VII together with a former analysis quoted from de Villiers (1951).

TABLE VII.

ANALYSES OF BRAUNITES.

No:-	H.R.165	H.R.106	H.R.112(a)	H.R.111(a)	de Villiers
Ore Type	Coarse-grained	Medium-grained	Porous	Medium-grained	-
Locality:	Labusrus	Bosrand	Otjosondu	Otjosondu	-
% SiO_2	9.61	9.25	9.14	9.43	9.94
% Al_2O_3	1.68	0.59	0.39	0.44	1.72
% Fe_2O_3	8.30	13.73	6.17	6.20	23.59
% MnO	39.23	39.88	41.74	40.05	59.07
% MnO_2	38.69	35.00	41.30	40.86	-
% BaO	0.37	0.55	0.57	0.59	-
% CaO	1.18	0.88	1.06	1.76	0.00
% MgO	0.46	0.76	0.36	0.64	0.31
% B_2O_3	0.21	0.13	0.14	0.23	0.20
TOTAL:	99.73	100.77	100.87	100.20	100.14
% Mn Metal	54.82	53.00	58.42	56.83	45.74

The mineral braunite gives rise to ores of good grade and, as can be seen from the table, the pure mineral carries up to 58% manganese metal.

The analysis given by de Villiers (1951) shows a very

high iron content, indeed he states "The iron content of the analysed braunite is ..... higher than that of any other braunite yet analysed". The present analyses show far lower values for Fe_2O_3, the average being about 8% as compared with 23.59% in de Villiers assay. The value of 13.73% Fe_2O_3 for braunite from Bosrand compares well with the figures of 13.05% and 15.57% obtained by Ödman (1950), and Hewett and Schaller (1937) respectively. The mineral from Bosrand may thus still be ferrian braunite, but the value given by de Villiers would seem to be due to admixed haematite or jacobsite.

The boron content of braunites is an interesting problem which has led to a significant amount of research. Studies by Wasserstein (1943) and Landergren (1945,48) have shown that this element is a common constituent of braunite ores. The former geochemist goes so far as to state that boron is a constant companion of braunite. Wasserstein's figures for this element range from 0.093% to 0.37%, whereas those from Ultevis gave values between 0.004% to 0.008% B. The value of boron reported by de Villiers (1951) in the braunite analysed from Otjosondu is 0.08% B. The samples from Otjosondu H.R.165, 106, 111(a), 112(a) all show boron values of less than 0.10%. Two further samples H.R. 20 and 115, both of which are very coarse braunites from Otjosondu, were studied spectro-chemically for the presence of trace elements by Mr. Russel of the Geological Survey, who was unable to detect boron in either sample. It would appear that the spectrographic method is more reliable than wet analysis when such small amounts of element are to be detected; furthermore, glass-ware is known to contribute traceable amounts of boron to analyses. It must therefore be concluded that boron is not a constant element in the braunite lattice.

TABLE VIII.

X-RAY DATA OF BRAUNITES.

Braunite (A.S.T.M.Index)		Braunite (A.S.T.M.Index)		Braunite (Otjosondu)	
o A	I	o A	I	o A	I
4.65	5	4.65	20	4.69	5
3.46	10	3.45	50	3.49	10
3.33	5	3.33	20	3.34	17
2.96	5	2.95	30		
				2.88	5
2.69	100	2.72	100	2.71	100
2.34	20	2.36	60	2.36	10
2.14	20	2.14	60	2.14	40
1.87	5	1.88	30		
1.76	5	1.76	30	1.742	5
1.82	5	1.82	20		
1.80	5	1.80	20		
1.76	5				
1.65	70	1.66	90	1.665	50
1.53	10	1.54	30	1.541	15
1.50	10	1.49	50	1.513	5
1.46	10	1.46	30	1.454	5
1.42	30	1.42	80	1.422	25
1.37	5	1.37	30	1.358	22
1.35	10	1.35	50	1.355	12
1.27	5				
1.17	5	1.17	20		
1.17	5	1.17	20		
1.15	5	1.15	10		
1.08	20	1.08	60	1.078	20
1.05	10	1.05	50	1.048	20

The X-ray patterns obtained from the various braunites show little difference in "d" value spacings which, as can be seen from Table VIII, are very similar to published values for the mineral. In the case of differential thermal analysis, no diagnostic peaks are observed on the curves; the downward trend noted in the case of braunite in figure 8 is due to variation in conductivity of the material.

(b) Jacobsite. $(Mn\ Fe)_3O_4$.

This mineral is dominant in the poorer ores of the area. Following Mason's (1943) classification jacobsite includes all those specimens of $(Fe\ Mn)_3O_4$ containing between 16.7 and 54% Mn_3O_4. Above 54% Mn_3O_4 the mineral is

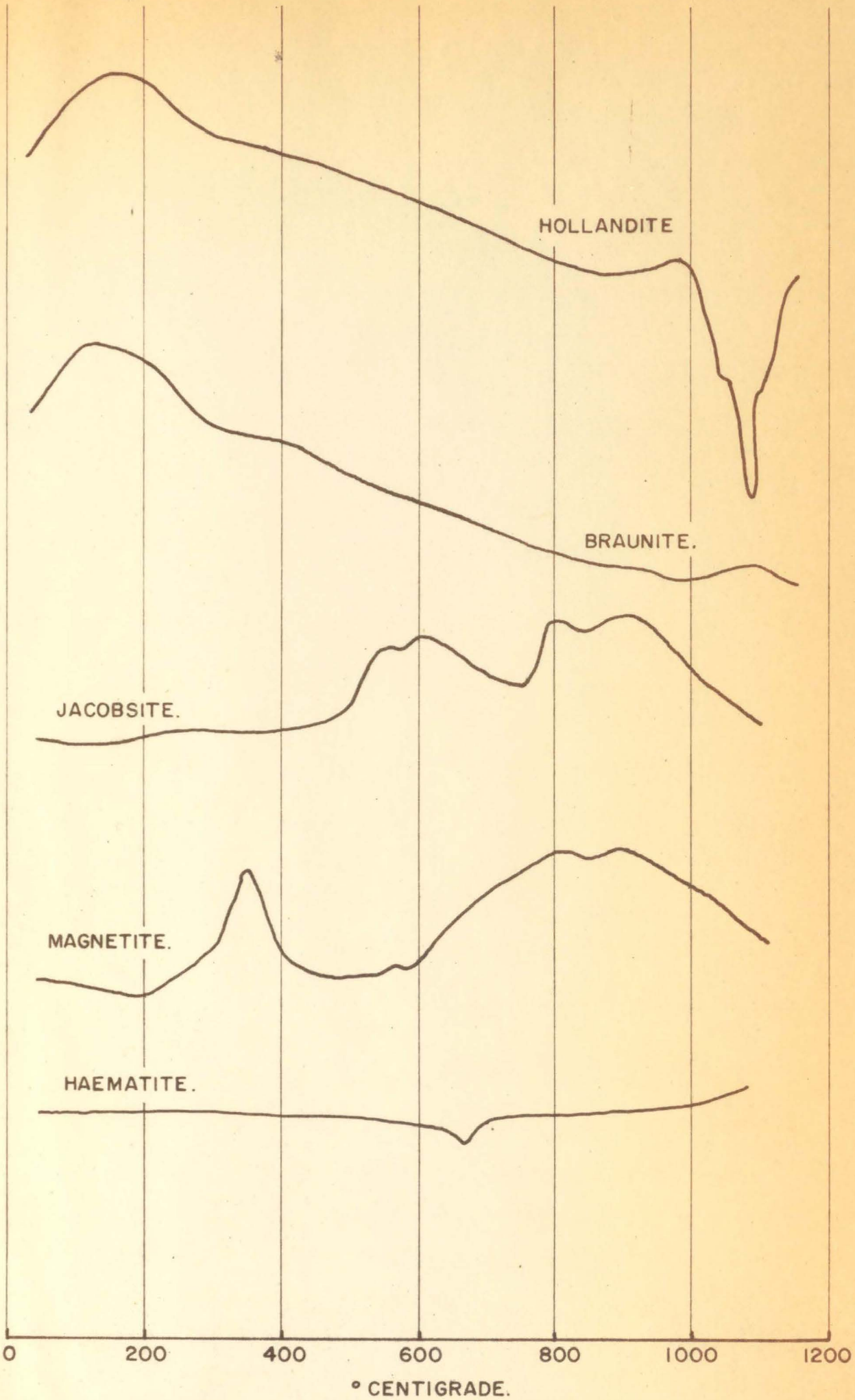


FIGURE 8

DIFFERENTIAL THERMAL ANALYSIS OF ORE MINERALS.

demonstrably seen to be accompanied by hausmannite and then is known as vredenburgite, and when 91% Mn_3O_4 is present in the mineral, hausmannite alone is noted. Below 16.7% Mn_3O_4 the mineral formed is magnetite. The percentage of jacobsite and vredenburgite varies considerably from specimen to specimen, some containing over 90% while others show less than 10% of the magnetic mineral.

After careful fractionation, three specimens of jacobsite were analysed, the results being given in Table IX.

TABLE IX.

ANALYSES OF JACOBSITES.

No:	H.R.106(a)	H.R.109	H.R.113
Locality:	Bosrand	Labusrus	Ebenezer
% SiO_2	1.42	2.01	0.17
% Al_2O_3	1.99	2.80	0.57
% Fe_2O_3	52.53	40.24	52.95
% MnO	27.66	29.94	33.37
% MnO_2	16.30	23.26	12.39
% MgO	0.56	1.39	1.04
TOTAL:	100.46	99.64	100.49
% Mn Metal	31.72	37.89	33.49
% Mn_3O_4	44.05	52.61	46.50

The jacobsite H.R.106(a) and the braunite H.R.106 were obtained from the same specimen. It is striking that whereas the braunites of the area contain 53 to 58% Mn metal the jacobsites carry only about 35% Mn, and it is thus obvious that the greater the amount of jacobsite present, the lower the grade of ore. Since the jacobsite is strongly magnetic the good ore can generally be easily differentiated from the bad by this property with the aid of a small magnet.

The X-ray data obtained on four samples of jacobsite are presented in Table X. Using five lines the unit cell measurements (a_o) were calculated (Henry et al 1951), and have been found to vary. Two jacobsite patterns from the A.S.T.M. index are included in the table for comparison. The first of these jacobsites is low in magnesium, whereas the second is a synthetic magnesium jacobsite. The relevant lines for magnetite, and the calculated cube edge value is also included for comparison.

The variation in the unit cell measurements of the jacobsites finds no ready explanation when it is considered that both Fe^{2+} and Fe^{3+} can be replaced by Mn^{2+} and Mn^{3+}, and the presence of Mg^{2+} as the magnesioferrite molecule causes further complications. However, it appears that as the MgO value increases the cell shrinks, and as the amount of manganese decreases, the cell also becomes smaller.

A typical differential thermal analysis curve for jacobsite from the area is given in figure 8.

Schmidt and Vermaas (1955) have shown that oxidation phenomena cause similar exothermic peaks in the case of magnetites, and there is little doubt that exactly the same phenomena are active during the heating of jacobsite. Comparing the curves for magnetite and jacobsite (figure 8) it is noted that surface oxidation effects take place at 350°C in the case of magnetite, whereas the first exothermic peak in the case of jacobsite begins at about 450°C. It has been noted in polished sections that the edges of jacobsites are occasionally replaced in part by haematite, but this is considered to be due to pneumatolytic action. It appears however that the lower temperature of reaction has been exceeded during metamorphism. In the case of magnetite, this mineral has been entirely altered to haematite in the ores, itabirites, and even in the quartzites of the area. The second exothermic reaction of magnetite has been found

TABLE X.

X-RAY DATA OF JACOBSITES.

hkl	Jacobsite (A.S.T.M. Index)	Jacobsite (Otjosondu Area)	Jacobsite (Otjosondu Area)	Jacobsite (Otjosondu Area)	Jacobsite (Otjosondu Area)	Magnesian Jacobsite (A.S.T.M. Index)	Magnetite (A.S.T.M. Index)
	Å	Å	Å	Å	Å	Å	Å
220	3.02	3.01	3.00	3.00	2.98	2.98	2.97
311	2.58	2.564	2.560	2.564	2.518	2.54	2.53
400	2.13	2.120	2.120	2.120	-	2.11	2.097
422	1.743	1.734	1.732	1.726	1.720	1.72	1.714
440	1.510	1.502	-	1.500	1.500	1.49	1.484
a_o	8.515	8.498	8.487	8.478	8.421	8.42	8.391

by Schmidt and Vermaas (1955) to be accelerated at about 580°C, and they suggest that the transition from ferromagnetism promotes the diffusion of oxygen into the lattice and this reaction leads to the complete alteration of magnetite to haematite. The corresponding reaction in the case of jacobsite appears to commence only at 750°C, and, as the jacobsite has not to any noticeable extent reverted to hausmannite and haematite it appears that the conditions of metamorphism which altered the primary manganese sediment corresponded to a temperature between 580°C and 750°C at the pressure of 1 atmosphere. It is assumed that a sufficient supply of oxygen was available for both the alteration of magnetite to haematite and jacobsite to haematite and hausmannite. It is interesting to note that de Villiers (1951), using vredenburgite as an index mineral, found the minimum temperature of formation to be 500°C.

(c) Hausmannite (Mn_3O_4)

Hausmannite appears as ex-solution lamellae in vredenburgite and secondly in small grains within the same mineral. It is very easily replaced by the supergene minerals psilomelane and pyrolusite. Unfortunately, this mineral could not be obtained in a sufficiently pure state for chemical analysis and further study.

(d) Vredenburgite $(Mn\ Fe)_3O_4$.

The vredenburgite ores of the Otjosondu area are generally associated with jacobsite-rich types from which they can be differentiated by their very well developed cleavage. They are very difficult to polish as chipping takes place easily. An analysis of vredenburgite from Otjosondu, together with partial analyses of two Indian vredenburgites quoted from Fermor (1909) and another from de Villiers (1951), are listed in Table XI.

TABLE XI.

ANALYSES OF VREDENBURGITES.

No:	H.R.105	1080	A.346		
Locality:	Bosrand	Beldongri	Garividi	Otjosondu (de Villiers)	
% SiO_2	4.00	1.77	.20	% SiO_2	1.04
% Al_2O_3	1.29	1.32	2.10		
% Fe_2O_3	47.27	28.85	31.29	% Fe	22.73
% MnO	32.57	38.24	38.53	% Mn	39.74
% MnO_2	14.35	23.67	24.94		
% MgO	0.56	0.99	1.20		
Total:	100.04	94.84	98.26		
% Mn Metal	34.29	44.57	45.60		39.74
% Mn_3O_4	47.62	61.89	63.32		55.18

It is noted in these analyses that the MnO_2:MnO ratio appears to be lower in the Bosrand specimen than for the other specimens. Furthermore, the percentage Mn_3O_4 is only 47.62%. Mason (1943) shows that at ordinary temperatures there is an area of immisicibility between 54% and 91% Mn_3O_4, but this specimen, which under the microscope appears to be pure vredenburgite, shows immisicibility phenomena even though the Mn_3O_4 percentage is less than Mason's lower limit. The presence of 4% SiO_2 is also considered to be high, however if braunite were present as an impurity it would probably increase the Mn content of the sample. It is further noted that de Villiers (1951) analysis of vredenburgite is only slightly above the lower immisicibility value determined by Mason. It is suggested, therefore, that although immisicibility is only noted between 54% and 91% Mn_3O_4 under laboratory conditions, unmixing may be promoted in vredenburgites by factors such as stress. As the Otjosondu mineral shows definite exsolution lamellae of hausmannite in jacobsite it must still be considered vredenburgite.

Many of the ores carry coarse jacobsite-hausmannite intergrowths, and this vredenburgite is generally associated with iron-rich ores as opposed to those rich in braunite.

(e) Bixbyite Mn_2O_3.

The difficulty of identification of this mineral when accompanied by braunite is mentioned by several mineralogists and, although every care was taken to check its presence, it appears that when compared with the amount of braunite in the ores this mineral is virtually absent. It was, however, identified in a few specimens, but detection by chemical analysis was impossible. de Villiers (1943) suggested that bixbyites should be divided on the basis of Mn:Fe ratios into the bixbyite-sitaparite-partridgeite mineral series. He concluded, on the basis of etch tests that the Otjosondu mineral was partridgeite. This suggests that the mineral is low in iron i.e., less than 10% Fe_2O_3. Mason (1943, 1944) in two papers discussed bixbyite and came to the conclusion that from a paragenetic viewpoint the bixbyites are of two types:-

(1) those with an Fe_2O_3 content of 45 to 60% which appear in deposits of pneumatolyitic origin and

(2) those with an Fe_2O_3 content of 0 to 30% occurring in metamorphosed manganese ores.

It appears thus that if de Villiers' deductions, which are based on etch tests, are well founded, then the bixbyites of Otjosondu fall into the second group and this fits in well with field evidence. The final proof awaits the finding of a specimen of bixbyite sufficiently pure to allow of a reliable chemical analysis.

(f) Hollandite $Ba\ (Mn\ Fe)_8O_{16}$.

Hollandite is a minor constituent of some of the ores of Otjosondu, but in one working it forms 40% of the ore by weight, the remainder being braunite. This mineral was separated from the braunite and chemically

analysed. As a rule, the ores containing hollandite can be distinguished by their bright submetallic lustre and the obvious orientation of crystals of this mineral. Properties of hollandite from Otjosondu were given by de Villiers (1951) and these he compared with Indian hollandite. He concluded that differences between the two were due to the abundance of iron in the South West African mineral. The chemical analysis given in Table XII refutes this statement and for comparison a few analyses showing the more important elements given by Fermor (1909) for Indian hollandites are included. Hollandite H.R.111 and Braunite H.R.111(a) were separated from the same specimen.

TABLE XII.

ANALYSES OF HOLLANDITES.

No:	H.R.111	-	1146	752	1062
Locality:	Otjosondu	India	Balaghat	Govari	Juawani
% SiO_2	0.28	Tr.	1.40	-	-
% Al_2O_3	0.93	0.94	1.04	0.42	1.09
% Fe_2O_3	6.23	10.56	4.43	5.73	9.26
% MnO	7.47	5.12	9.02	14.20	9.09
% MnO_2	63.26	65.63	75.05	71.25	72.44
% BaO	21.17	17.59	2.96	7.22	5.55
% B_2O_3	0.17	-	-	-	-
Total	99.51	99.84	93.90	98.82	97.43
% Mn Metal	45.76	45.44	54.41	56.02	52.81

Although difficulty has been reported in obtaining X-ray diffraction patterns of hollandite from Otjosondu using photographic methods and manganese filtered iron radiation, a very satisfactory trace was obtained using nickel-filtered copper radiation on a goniometric recorder. The "d" values thus obtained are tabulated in Table XIII together with standard patterns. It is noted that a few strong lines present in the case of standard patterns are absent in the

case of the Otjosondu specimen. It is doubtful whether this could be due to absorbtion of the X-rays, but it may yet prove that the very high BaO content of the Otjosondu hollandite explains both this phenomenon and differences noted by de Villiers. The few lines noted by de Villiers (1951) as determined by J.W. van Niekerk are included for comparison. A d.t.a. curve is given in figure 8.

TABLE XIII.

X-RAY DATA OF HOLLANDITES.

Hollondite (A.S.T.M.Tables)						Hollondite, Otjosondu				Hollondite India (de Villiers)	
						Roper		de Villiers			
o A	I	o A	I	o A	I	o A	I	o A	I	o A	I
3.53	90	3.51	60	3.54	80	3.54	25				
3.47	90	3.47	10	3.47	80	3.45	21				
3.18	90			3.18	80	3.20	35				
3.14	100	3.13	90	3.14	100	3.14	100	3.13	100		
3.11	100	3.11	90	3.12	100	3.10	85	3.09	100	3.10	100
3.08	90			3.08	80	3.06	30			3.06	100
						2.80	5				
2.75	10	2.76	20	2.75	5						
2.71	10			2.71	10	2.71	5				
						2.61	5				
2.50	60	2.48	30	2.51	40	2.51	11				
		2.45	20								
2.41	90	2.40	90	2.41	80	2.41	17	2.40	80	2.39	80
2.34	10			2.34	5						
2.24	20			2.23	10	2.26	8				
2.20	90	2.20	100	2.20	80	2.21	41	2.20	50	2.19	[illegible]
2.18	90	2.17	90	2.17	80	2.18	7	2.17	50	2.16	50
2.15	90	2.15	90	2.15	80	2.15	6	2.15	50	2.13	50
		1.98	20								
2.00	20	1.97	20	1.99	10	1.980	7				
1.97	60	1.95	40	1.96	40						
1.90	10	1.92	40	1.90	5						
1.86	90	1.84	90	1.86	80						
1.85	60	1.83	90	1.84	40					1.841	30
1.83	60			1.83	40						
1.82	90			1.82	80	1.814	5			1.810	30
1.76	20	1.75	20	1.76	10	1.769	4				
1.73	20	1.73	20	1.72	10	1.723	5				
		1.68	60			1.700	10				
1.67	90	1.65	90	1.66	80	1.677	25	1.662	60	1.656	60
1.62	60	1.63	90	1.62	40	1.615	20				
1.565	20	1.550	20	1.56	10	1.570	45				
1.560	90	1.543	90	1.55	80	1.552	5	1.549	50		
1.540	90	1.539	90	1.54	80	1.541	6	1.536	50	1.539	50
1.528	20	1.530	20	1.53	10					1.533	50
1.440	60	1.435	60	1.44	40						
1.412	10	1.419	10	1.41	5	1.421	5				
		1.400	10								
1.372	20	1.37	10	1.37	10	1.377	7				

The hollandite present in the ores is considered to have formed by dehydration of psilomelane during metamorphism This transformation is stated by Fleisher and Richmond (1943) to take place between 500 and 600°C, and, as the reaction is complete it gives an indication of the lower temperature limit of metamorphism. This value corresponds well to the 580 to 750°C range deduced from other minerals.

(g) Pyrolusite (MnO_2) and Psilomelane ($Ba\ Mn_9O_{18}2H_2O$).

The minerals pyrolusite and psilomelane are formed from the primary ore minerals by supergene agencies and are so often found together that they may for convenience be described at the same time. The amounts of these minerals generally decrease within a depth of a few feet: thus they do not represent any considerable enrichment even at the surface. On the other hand, one or two ore bodies which generally lie on the flats, rather than near the small quartzite outcrops, showed enrichment to a depth of over 20 feet. Generally, however, enrichment features are not marked.

Pyrolusite and psilomelane occur as small veinlets passing through most of the ore minerals and replacing them. Occasionally near small faults porous-textured "coke-like" ore is found. This texture is due to the leaching of most of the primary minerals with the development of the peroxides. The first primary mineral to suffer replacement is hausmannite followed by jacobsite, but in all these ores occasional crystals of highly resistant braunite are observable.

It is noteworthy that these porous ores carrying pyrolusite and psilomelane are generally patchy in nature and relatively small in amount. Those found at depth in boreholes are probably due to percolation of water through the ore by way of fractures and do not in the opinion of the author represent extensive oxidized patches near a

former water table.

The secondary nature of these two minerals causes their X-ray diffraction patterns to be very diffuse and the interpretation of these are difficult, only the strongest of the lines permitting measurement.

(h) Chalcophanite (Mn Zn) $0.2MnO_2.2H_2O$

This mineral occurs but rarely in the ores of Otjosondu. Under the ore microscope it shows plumose texture, but generally assumes a rather bad polish when associated with the harder manganese minerals. There is every indication that lead-manganese minerals should also occur in the ores; however, up to the present time none have been noted.

(i) Haematite Fe_2O_3.

This mineral, although not strictly an ore, may be described more conveniently with the ore minerals than with the gangue materials. Haematite is found occurring in two ways, firstly as a major component in the itabiritic schists and, secondly, as a minor component of the manganese ores.

(i) Haematite in the schists: Although this haematite is not an ore mineral in the classical definition, the factor of geographical inertia may eventually lead to its extraction as an iron ore. Joubert (1952) refers briefly to this possibility. He states that: "The ores and their geological setting bear close resemblance to the itabirites of Windhoek and Walvis Bay, and appear to be only a manganiferous variant of these. No attempt has yet been made to assess this occurrence from the aspect of iron content; the iron and manganese combined will probably amount to one million tons per meter of depth. Most lenses are large enough to permit cheap opencast mining with the use of mechanical equipment". After mining, the ore would have to be concentrated mechanically and although the

schistose ore would lend itself well to such a process, a market will first have to be found for such a fine grained product, or sintering or briquetting processes will have to be used.

(ii) Haematite in the manganese ores: The haematite in the manganese ores occurs in two ways, firstly as late replacement of the manganese-iron minerals and, secondly, as veins and blebs of pure specularite.

Replacement of earlier manganese-iron minerals, especially jacobsite, by haematite has taken place only to a small extent. Late introduction of iron accounts for most of the replacement.

The greatest amount of haematite is found as veins and blebs within the ore, crystals of purest specularite of over six inches being fairly common. The crystals often show well developed widmanstätten structure and are uncontaminated by manganese. Generally the veins of haematite are oriented in specific directions related to fractures which must have been present in the already re-crystallized manganese ore. This fact, together with the observation that close to the veins the manganese minerals have been attacked and replaced to a small extent by iron-bearing fluids, indicates that the phenomena are related to the pegmatites of the area. The iron was dissolved from the schists by the heated fluids and later deposited within the ore horizon. The preferential leaching and redeposition of iron in preference to manganese has its explanation in the rock types attacked, as well as in the chemical and physical nature of the fluids.

2. Gangue Minerals.

Two papers have been written by Vermaas on the garnets (1952) and the barium felspars (1953) of the ores. These two groups of minerals are by no means the only

gangue, for manganese-bearing pyroxenes, amphiboles and chlorite are also present, and many silicates, which do not carry manganese, contaminate the ores. Description of the gangue minerals falls logically into two sections, i.e. those carrying manganese, and those which do not.

(a) Manganese-bearing Gangue Minerals.

(i) Manganese Pyroxenes.

Manganese pyroxenes are ubiquitious within the silica-rich ores of Otjosondu. They form an important portion of certain ores, and occur also within the pegmatites and in the schists near the contacts of ore bodies.

The pyroxenes may be convienently subdivided into two groups:

Colourless and pink pyroxenes.

Brown, yellow and green pyroxenes.

Colourless and pink pyroxenes.

These pyroxenes have been identified as members of the wollastonite-rhodonite-bustamite series (Plate L). As a rule large 2V values are obtained from these pyroxenes thus identifying them as rhodonite; however, in certain sections low 2V angles have been measured indicating bustanite.

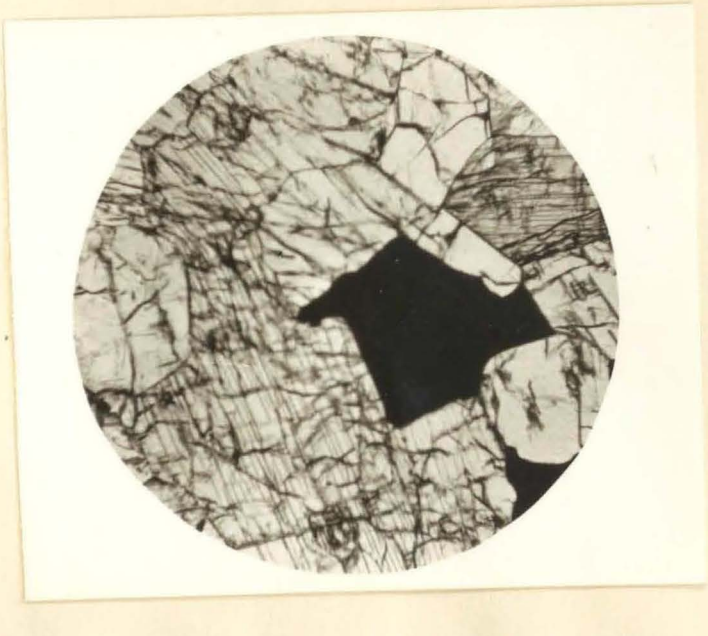


Plate L. Rhodonite.
The photomicrograph shows a thin section of rhodonite (Rh) with braunite(Br).
(Plane Polarized; x 30).

The members of the rhodonite series, which belong to the triclinic system, are practically omnipresent in the silicious ores. They are often intimately associated with calderite garnet, and braunite, but are also found to accompany jacobsite-rich ores. The minerals vary in amount within the ores from a few small scattered crystals to over half the bulk of the sample. They are easily overlooked in a cursary observation of the ores, as they are often replaced, and therefore blackened, by secondary manganese oxides. Massive pieces of black rhodonite have been found to carry crystals over two inches long and one inch wide (Plate LI). In thin section the black colour is seen to be due to incipient replacement of the mineral along very finely spaced cleavages. On prolonged boiling in dilute hydrochloric acid small chips revert once more to their original colour.



Plate LI. Rhodonite.
The photograph shows a typical hand specimen of blackened rhodonite. The large crystals should be noted.
(Scale in centimeters).

The X-ray data obtained from a specimen of rhodonite from Otjosondu is presented in Table XIV, The comparative "d" values and intensities given for rhodonite are obtained from the A.S.T.M. Index cards.

TABLE XIV.

X-RAY DATA OF RHODONITE.

Rhodonite (A.S.T.M. Index)		Rhodonite (Otjosondu)	
Å	I	Å	I
3.54	20	3.55	100
3.34	40	3.46	5
3.08	60	3.33	20
2.97	90	3.14	17
2.94	100	3.09	17
2.76	80	2.97	50
2.60	80	2.77	7
2.52	20	2.65	10
2.47	10	2.60	5
2.37	30	2.50	15
2.22	20	2.37	30
2.17	20	2.18	15
2.11	20	2.11	7
2.06	20	2.08	7
1.887	40	1.890	5
1.832	20	1.694	5
1.722	20	1.665	10
1.685	30	1.612	5
1.610	10	1.584	5
1.554	60	1.424	20
1.476	30		
1.427	60		

Optical constants determined on the pink pyroxenes are:-

Rhodonite		Bustamite	
α	= 1.716	α	= 1.672
β	= 1.721	β	= 1.686
γ	= 1.728	γ	= 1.687
$2V\gamma$	= 72°	$2V\gamma$	= 41°

Brown, yellow and green pyroxenes.

The brown, yellow and green pyroxenes of the area generally occur either within the pegmatites or in ores close to them where pneumatolytic action has taken place.

Generally all the brown, yellow and green pyroxenes near the ore bodies carry some manganese, and a division is made on the following basis:

Brown and Yellow Pyroxenes:

Johannsenite: $MnO.CaO.2SiO_2$ with subordinate $MgO.CaO.2SiO_2$ and $FeO.CaO.2SiO_2$

Schefferite: $MnO.SiO_2.FeO.SiO_2$ with subordinate $CaO.SiO_2$ and $MgO.SiO_2$

Urbanite: $CaMgSiO_3$ and $2NaFe(SiO_3)_2$ with Mn replacing the protoxides.

Green Pyroxenes:

Mangan-hedenburgite: $CaFe(SiO_3)_2$ with Mn replacing

Although the above subdivision appears simple, the accurate determination of these minerals is extremely difficult without detailed chemical analysis. Before any of the minerals were accepted as belonging to the above groups, a sample, free of inclusions, was boiled for a few minutes in dilute hydrochloric acid to remove any secondary manganese oxides, and subsequently fused on a loop of platinum wire and tested for the presence of Mn. The intetensity of reactions for this element naturally varied, but in almost every pyroxene tested a certain amount of manganese was found to be present.

Optical properties are unfortunately of little help in determining absolute composition in the above groups, as the variation in alkalies and the complicated substitution between groups, as well as within groups themselves, renders this a wellnigh impossible task.

Probably the most abundant and interesting group of pyroxenes is the urbanite group. These have obviously been formed by the pneumatolytic action of soda-bearing fluids on the ore. The optical constants vary greatly within the group.

The relationship between this mineral and acmite is shown in Table XV, where the "d" spacings of acmite and urbanite are given.

TABLE XV.

X-RAY DATA OF URBANITE AND ACMITE.

Acmite (A.S.T.M. Index)		Urbanite (Otjosondu)	
Å	I	Å	I
6.5	40	6.43	50
4.43	40	4.44	40
3.64	7		
		3.26	20
2.99	100	3.22	50
2.91	40	3.01	80
		2.93	100
2.54	60	2.56	50
2.48	27	2.53	30
2.20	20	2.50	15
2.12	20	2.14	30
		2.13	20
2.03	20	2.10	40
1.98	7	2.03	10
1.93	7		
1.73	13	1.95	5
1.68	7	1.75	90
1.66	7	1.67	10
1.63	7		
1.61	7	1.62	10
1.54	7	1.61	30
1.51	13	1.54	20
1.47	7	1.48	20
1.40	13	1.41	10

Johannsenite and schefferite are less abundant than urbanite, from which they can be distinguished by extinction angles. A pale green, somewhat pleochroic mineral having optical properties close to hedenburgite was found to give reactions for manganese. It was accompanied in the hand specimen by barium felspar and garnet.

Properties of the brown, yellow and green pyroxenes are given in Table XVI.

An interesting sidelight on the pyroxenes in the pegmatites, is that they are often altered by later pneumatolytic action, to a bright yellow powdery mineral

TABLE XVI.

PROPERTIES OF THE BROWN, YELLOW AND GREEN PYROXENES.

Mineral	Rock in which found	Colour in hand specimen	Pleochroism	Extinction Angle	Refractive Indices
Urbanite	Pegmatite	Brown to yellow	α - brown β - yellow brown γ - light yellow brown	$\gamma \wedge c = 18^{\circ}$	α 1.744 β 1.752 γ 1.763
Urbanite	Pegmatite	red-brown	α - brown β - reddish brown γ - orange	$\gamma \wedge c = 19^{\circ}$	
Schefferite	Pyroxene-quartz-microcline gneiss	brown	α - yellow brown β - brown γ - brown	$\gamma \wedge c = 45^{\circ}$	α 1.688 β 1.698 γ 1.720
Johannsenite	Pyroxene-quartz-felspar gneiss	brown	α - brown β - light brown γ - reddish brown	$\gamma \wedge c = 45^{\circ}$	α 1.712 β 1.721 γ 1.740
Manganhedenburgite	Pyroxene-quartz-haematite schist.	green	α - green β - brownish green γ - green	$\gamma \wedge c = 50^{\circ}$	α 1.730 β 1.736 γ 1.750

which,was identified by X-ray techniques to be nontronite, an iron rich member of the montmorillonite clay mineral group. The surrounding felspar appears to be completely fresh and unaltered by the fluids.

(ii) Manganese amphiboles.

A manganese amphibole, pleochoric in blue and pink, was found close to a pegmatite within the Ann Workings. Manganese amphiboles are rare within the or bodies and were it not for the striking purple colour of the hand specimen this small occurrence would no doubt have been overlooked.

It appears that this amphibole may be a new variety. It is pleochroic in blue and pink, shows intense dispersion but has low birefringence. In white light extinction does not take place, but anomalous blue colours appear on rotation of the slide. Furthermore, the crystals appear zoned and thus the optical characteristics are difficult to determine. The single factor which suggests that it is different from the manganese amphiboles so far described is the fact that the extinction angle is as high as 44°. The indices of refraction, and the pleochroic scheme are close to that for Winchite, however $\gamma\wedge c$ for the latter is at most 26°.

The only other amphibole from the area, having a similar appearance, occurs in the schists. It is the soda amphibole glaucophane, and it is light blue to colourless in thin section. Extinction angles of more than 7° were not measured on this mineral. It is, however, probable that the manganiferous mineral is a soda amphibole in which manganese proxies for iron. The X-ray data for these two minerals are given in Table XVII, and the optical data for these and for Winchite are given in Table XVIII.

TABLE XVII.

X-RAY DATA OF BLUE AND PURPLE AMPHIBOLES FROM OTJOSONDU.

Purple Manganese bearing Amphibole		Blue Amphibole (Glaucophane)	
o A	I	o A	I
8.35	100	8.29	100
4.77	5	4.72	7
4.49	7	4.49	9
		4.44	8
4.20	12	4.17	9
		3.96	6
3.62	3		
3.50	4		
3.39	6		
3.33	10	3.37	20
3.26	20	3.25	22
3.11	89	3.15	68
2.95	6	2.90	9
2.80	85	2.78	48
2.71	17	2.71	11
2.59	7	2.56	5
2.53	10	2.52	6
		2.41	5
2.37	5		
2.32	5	2.31	18
2.28	3	2.23	3
2.16	18	2.16	8
2.06	5		
2.02	5	2.02	5
2.01	5	2.00	5
1.998	5	1.990	6
1.955	3		
1.890	5	1.875	11
1.679	3	1.671	11
1.654	9	1.646	10
1.630	5	1.630	5
1.613	3		
1.582	3		
		1.551	6
1.518	3	1.520	6
1.496	3	1.492	10
1.476	3		
1.430	8	1.419	9
1.372	3		
1.340	3		
		1.315	8
		1.284	5
		1.185	5

TABLE XVIII.

OPTICAL DATA OF THE BLUE AND PURPLE AMPHIBOLES OF OTJOSONDU

	Purple Amphibole	Blue Amphibole (Glaucophane)	Winchite
α	1.639	1.621	1.636
β	1.650	1.636	1.646
γ	1.666	1.638	1.658
$\gamma \wedge c$	44°	6°	18°

A manganiferous mineral (Plate LII), which in the hand specimen is honey coloured and occurs in an augen gneiss near the Ann ore bodies, may be dannemorite; however too little information is available to state this categorically. The mineral is generally badly altered by weathering, and too little pure mineral was available for detailed microscopic or X-ray work. The definite conclusion that dannemorite occurs at Otjosondu must thus await the finding of better specimens.

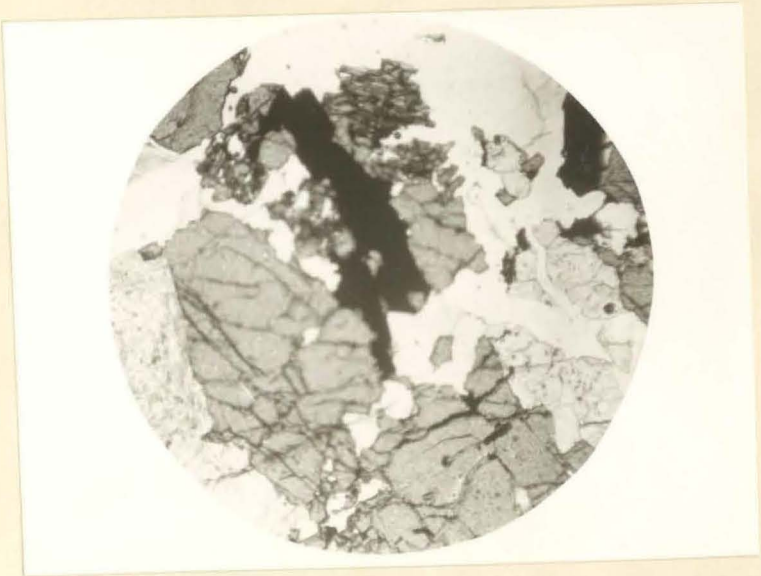


Plate LII. Dannemorite (?) (Dn) with calderite garnet (Cd) apatite (Ap), braunite (Br) and Felspar (Or). An altered honey-coloured fibrous mineral, probably dannemorite, is shown together with garnet, ore, apatite and orthoclase in a pegmatite.
(Plane Polarized; x 30).

(iii) Garnet.

The manganese-iron garnets of Otjosondu have been described by both de Villiers (1951) and Vermaas (1952), and most of the minerological work done by the author merely confirms their identifications, but the occurrence and appearance of these silicates warrants further comment.

There is a whole range of colours from reddish brown to light yellow in the hand specimen; however in thin section they are usually yellow, no bright red types being noted. They are often massive in appearance and form an interlocking mosaic with ore minerals and manganese pyroxenes. They occur as almost perfect crystals within the pegmatites and are also abundant near the contacts of schist and ore, where they bring into sharp focus the banded nature of the ores.

As a general rule garnets are high in the crystalloblastic series; however, they often enclose perfect crystals of braunite but irregular garnets are in turn found within granoblastic manganese minerals. Two important textures noted by de Villiers are the myrmekitic intergrowth of garnet and braunite, and films of garnet between braunite and vredenburgite. These textures will be discussed in more detail later.

It is worthy of note that the most important members of the garnet group at Otjosondu are:

Andradite	$3CaO.Fe_2O_3.3SiO_2$
Calderite	$3MnO.Fe_2O_3.3SiO_2$
Spessartite	$3MnO.Al_2O_3.3SiO_2$
Pyrope	$3MgO.Al_2O_3.3SiO_2$

The first three of these form the bulk of the garnets, only little of the pyrope molecule being present The Calderite molecule forms an appreciable percentage of the garnet of the ores, as is also the case in certain manganese deposits in India.

(iv) Manganese Chlorite.

A pink chlorite mineral, identified by means of X-ray diffraction on oriented specimens, was found near a pegmatite cutting the ore. Strong 7 and 14 Å spacings, which are unaffected by heating to 450°C, are noted in the diffraction pattern. The mineral gives a slight reaction for manganese and optical constants which could be determined are as follows:

$\beta = 1.574$ $\quad 2V = 12^{\circ}$.

(v) Manganese-bearing Biotite.

Several thin sections from contacts between schist and ore showed highly pleochroic biotite, which when tested gave a reaction for manganese.

(b) Non-manganiferous Gangue Minerals.

(i) Felspars.

One of the most important groups of minerals which form gangue within the manganese ores are the felspars. They may be divided into: (1) the sodic and potassic varieties, introduced by pneumatolytic action during the intrusion of the pegmatites, and (2) the barium-bearing felspars which occur as metacrysts within the ores.

Little need be said of the first except that they form veins within the ore and thus reduce its tenor. The latter (hyloplane-celsian) are fairly widespread throughout the ores and have not been observed to show any preferential association with silica-rich or jacobsitic types. They have been described fairly fully in a publication by Vermaas (1953), who noted that a complete range from Cn_{10} to Cn_{94} occurs within the ores.

It is obvious from their mode of occurrence that they are of metamorphic origin. The barium present in manganese deposits is generally found as the sulphate, but where temperatures are sufficiently high and potash, alumina and silica are available, the more stable felspar mineral forms.

It is, however, interesting to note that de Villiers observed large grains of barite within granitic material, suggesting that a direct influence of pegmatitic fluids on barium sulphate did not alter the mineral, thus substantiating the suggested metamorphic origin of the barium felspars.

(ii) Quartz.

Fine grained quartz introduced by supergene agencies is present in some of the weathered ores, and has replaced most of the silicate minerals in the upper few inches. Quartz also occurs as irregular gash veins in zones of tensile stress within the ore bodies. The quartz veins are accompanied by barite in many cases. Quartz is also observed as thin streaks and lenses within the hollandite-braunite ores of the Ann area, and in the braunite ores of the Jeppe area. This quartz was originally present as clastic grains within the unmetamorphosed ores.

Blue chalcedony, which probably owes its hue to a small amount of manganese, is present as a coating on a few specimens.

(iii) Barite.

Thin veins and isolated blebs of barite have been observed throughout the ores. de Villiers (1951) described barite grains in the granitic rocks of Otjosondu, but it is obvious from petrological and field evidence that the barite is not derived from pegmatitic sources, but had its origin in the manganiferous sediments.

(iv) Apatite.

Rare apatite, which shows normal optical properties, thus suggesting that manganese is not present in the lattice, was noted in a few ores. It generally accompanies garnet and occurs as scattered crystals within or in contact with the latter mineral, especially near pegmatites.

3. The Textures of the Ores.

A very general textural subdivision of ores can be made on the basis of macroscopic examination. In the first case the ores present a definite banded appearance which on field inspection is seen to parallel the strike of the surrounding sedimentary rocks. The banding is repeated under the microscope both in grain orientation and mineralogical variation. Certain of the ores, however, also exhibit in the hand specimen obvious crystalloblastic textures with a complete absence of banding. Generally they are then monomineralic. Under the microscope the latter group of specimens show a high degree of crystal development.

Certain of the microscopic textures of the ores have already been noted by de Villiers (1951); however, these will be re-described together with more detailed findings of the present work.

De Villiers (1951) states that the grains of one mineral generally cluster together to form fairly large sized bodies. This is often true on both macroscopic and microscopic scales when banded ores are excluded. Monomineralic braunite specimens for example, often exhibit coarse crystalloblastic textures (Plate LIII).

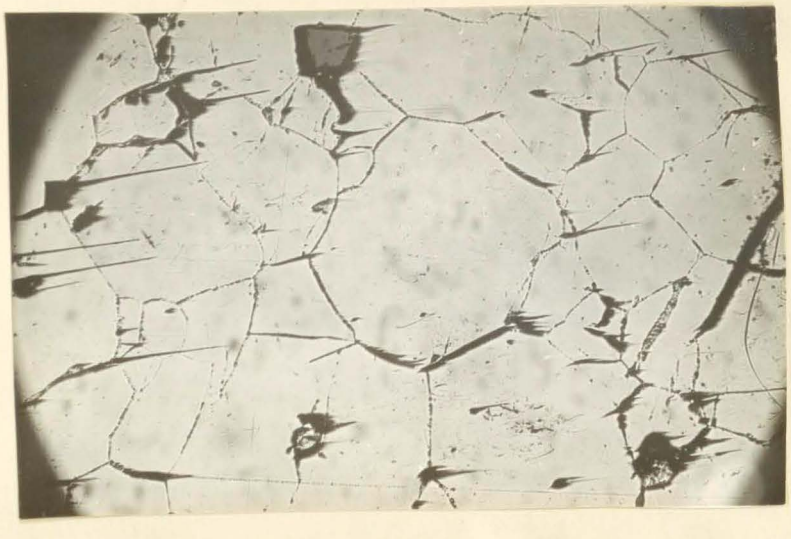


Plate LIII. Coarse Braunite.
The photograph shows the coarse crystalloblastic texture of a braunitic ore from Otjosondu.
(Polished section; reflected light x 30).

When the ore is banded, however, the statement is not true, for a single mineral has a greater distribution in two dimensions than in the third, with the result that an erroneous impression of the distribution of any particular ore mineral may be gained if the specimen is cut parallel to the banding.

It was further observed by de Villiers (1951) that when braunite and jacobsite (or vredenburgite) occur together, the latter minerals have a tendency to occupy interstices between comparatively well formed or somewhat rounded braunite crystals. He noted a similar relationship between braunite and garnet (Plate LIV). This has proved

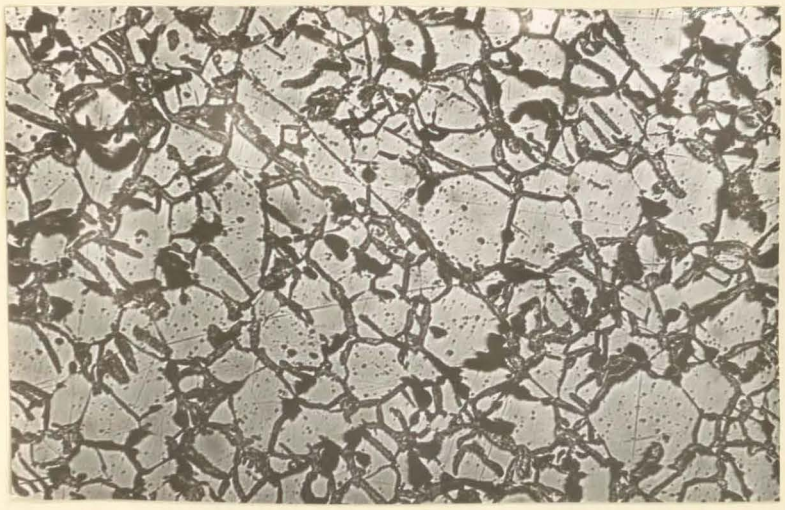


Plate LIV. Braunitic ore.
Fairly coarse grained crystals of braunite (Br) are surrounded interstitially by very fine rims of garnet and other gangue.
(Polished Section; reflected light; x 30).

correct in nearly all the sections examined, and has its explanation in the crystalloblastic series for the minerals present and in their temperature of formation. As a rule the highest members in the crystalloblastic series are braunite and hollandite, these two forming practically perfect crystals within all types of ore. These two minerals are followed by garnet and jacobsite.

Myrmekitic intergrowth of garnet and braunite, described by de Villiers (1951), has counterparts in similar intergrowths of braunite and rhodonite (Plate LV) and even garnet and rhodonite. No explanation for the

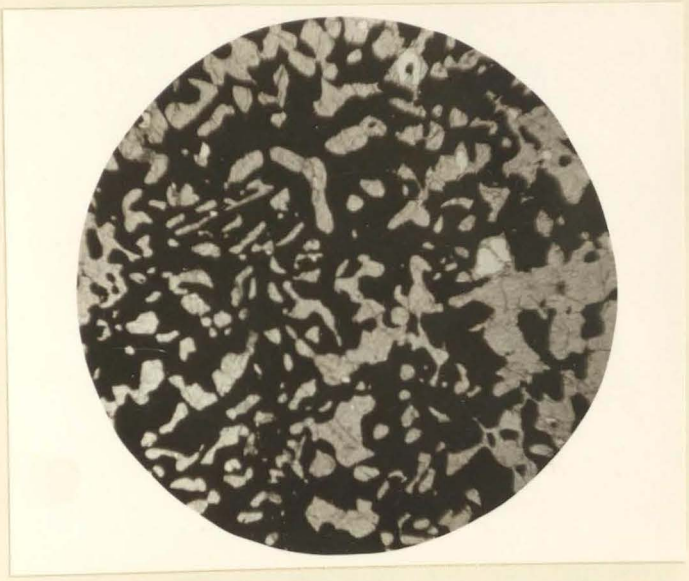


Plate LV. Myrmekitic intergrowth of braunite and rhodonite. The myrmekitic intergrowth of braunite (Br) and rhodonite (Rh) is considered to be caused by simultaneous recrystallization.
(Polished Section; reflected light; x 30).

intergrowth of garnet and braunite was given by de Villiers (1951), but all these structures are considered to be due to simultaneous recrystallization of the two minerals in each case (Plate LVI).



Plate LVI. Garnet and braunite.
The texture displayed by the light coloured braunite (Br) and dark coloured garnet is considered to be due to simultaneous recrystallization.
(Polished Section; reflected light; x 30).

de Villiers further noted that grains of vredenburgite are often separated by thin films of garnet from braunite, and suggested that this was due to the decomposition of braunite to form vredenburgite, garnet, and oxygen. The decomposition of braunite in such a manner is not indicated by differential thermal analysis, and another more probable origin must be sought. It is known that certain portions of the ore bodies were heated to higher temperatures than others, and that braunite is highest in the crystalloblastic series. It is furthermore observed that the garnet sometimes surrounds well developed crystals of braunite (Plate LVII).



Plate LVII. Garnet and braunite.
Well developed crystals of braunite (light) in garnet (dark).
(Polished Section; reflected light; x 30).

It is therefore considered that under the conditions of metamorphism braunite was the stable mineral containing silica, and any excess of this element was expelled in the form of a garnet rim around the braunite porphyroblasts. The garnet probably reacted at a further stage with more manganese to form braunite once more.

The fact that part of the haematite was apparently introduced after the crystallization of the manganese oxides has already been mentioned; it is due to the pneumatolytic

effect of pegmatitic fluids acting firstly on iron rich minerals, dissolving their iron, and then replacing the earlier formed manganese minerals or depositing haematite in fractures. The upper few inches of ore show a similar effect due to the action of supergene solutions.

Hollandite, which is rather difficult to polish in comparison with the other minerals in the suite, is associated, often in well formed crystals, with braunite. The two minerals generally exhibit well banded textures, the hollandite being present as bladed crystals (Plate LVIII).



Plate LVIII. Braunite - hollandite ore.
Bladed hollandite crystals (Ho) are accompanied by braunite (Br).
(Polished Section; Crossed Nicols x 30).

In this ore, ex-solution lamellae of hollandite have been noted in braunite crystals, but the reverse has not yet been observed. Other ex-solution textures are provided by hausmannite in jacobsite to form vredenburgite (Plate LIX).

Veined textures in the ores are as a general rule rare, but two types of veining have been noted. The first is known to be associated with pegmatitic action, and is confined to veins of pegmatite and haematite gangue in the ores (Plate LX). The second group of veins are due to supergene agencies and in this case secondary manganese



Plate LIX. Vredenburgite.
Ex-solution lamellae of hausmannite (white) in jacobsite (light grey) are seen to be oriented along the octohedral planes of the latter mineral.
(Polished Section; crossed Nicols; x100).



Plate LX. Haematite vein in ore.
One of the few veined textures of the ores is shown ih this plate. Late haematite (He, light) cuts garnet (Gr, dark grey) and braunite (Br, grey).
(Polished Section; reflected light; x 30).

oxides are found to vein into the primary ore minerals, enriching them to a certain extent. As the process of enrichment proceeds, garnet, jacobsite and vredenburgite become converted to the secondary minerals, but the braunite

crystals generally remain unaltered. (Plate LXI).

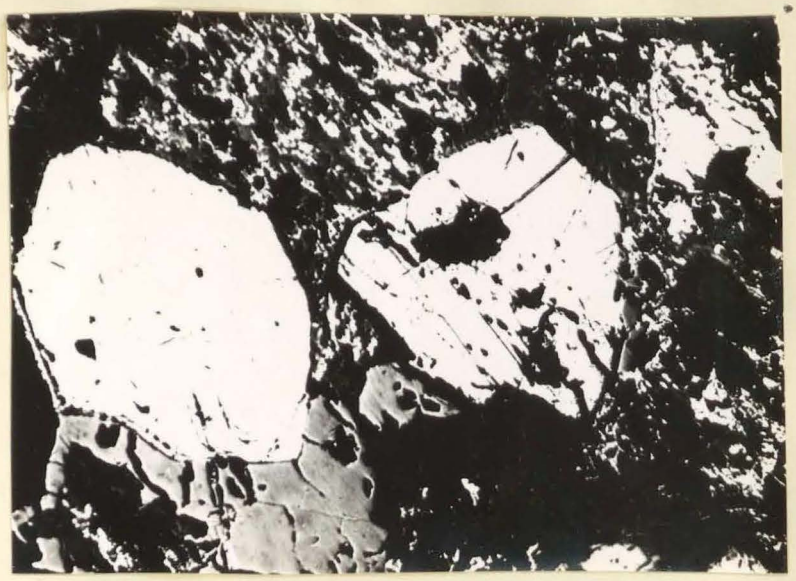


Plate LXI. Secondary ore.
Almost unaltered braunite (Br) crystals remain in a groundmass of partly altered jacobsite (J) and black psiolomelane and pyrolusite.
(Polished Section; reflected light; x 60).

Even in the most advanced stages of alteration partially altered braunite crystals are noted in the polished sections of the secondary ores (Plate LXII).



Plate LXII. Secondary Ore.
Skeletal crystals of braunite (Br) in earthy black psilomelane and pyrolusite. At this advanced stage of alteration all the ore minerals other than the braunite have been completely altered to the peroxides.
(Polished Section; reflected light; x 30).

"Iced cake" textures in which garnets have become cracked and filled with secondary manganese oxides are often observed in thin section. This is again attributable to supergene agencies, and is not a retrograde phenomenon.

4. The Metamorphism, Pneumatolysis and Subsequent Supergene Alteration of the Ores.

It is concluded from field observations, textural relationships, and trace element determination that the ores of Otjosondu were deposited as primary manganese sediments within an extremely thick sedimentary succession. As downwarping of the geosyncline took place the low temperature minerals became unstable and they reacted with one another or underwent phase changes which resulted in the present suite of high temperature minerals described.

The earliest and most important series of changes which took place were between silica and manganese. Braunite appears to have been the first high temperature mineral to form, but subsequently simultaneous recrystallization of this mineral and garnet occurred, thus resulting in the myrmekitic intergrowth of the two minerals. It appears from the ore study that jacobsite formed only when all the silica had reacted with manganese to form braunite, pyroxene or garnet. Ores carrying braunite and quartz only, have been noted in the Ann workings, but jacobsite is rarely noted together with quartz. A certain amount of garnet is definitely of later age than braunite for garnet is found enclosing euhedral braunite crystals. Rhodonite and celsian-hyalophane felspars also formed during this metamorphic period. The crystallization of the hollandite was probably contemporaneous with the early braunite, but hausmannite, vredenburgite, bixbyite and chalcophanite are all late metamorphic minerals.

When the formation of these minerals was complete, iron fluids associated with the pneumatolytic phase of the

pegmatites moved through the ores, depositing large haematite crystals (Plate LXIII) and also replacing to a small extent the manganese-iron minerals. A second generation



Plate LXIII. Haematite crystal.
A crystal of haematite deposited during the pegmatitic phase shows a well developed habit.
(Scale in inches)

of braunite also had its origin in pneumatolytic action of the pegmatites (Plate LXIV). Some of the rhodonite and



Plate LXIV. Braunite crystal.
A corresponding braunite crystal broken free from enclosing pegmatitic material shows striated faces.
(Scale as for LXIII).

garnets, together with the other manganese pyroxenes and amphiboles, are directly related to pegmatitic intrusions (Plates LXV and LXVI).

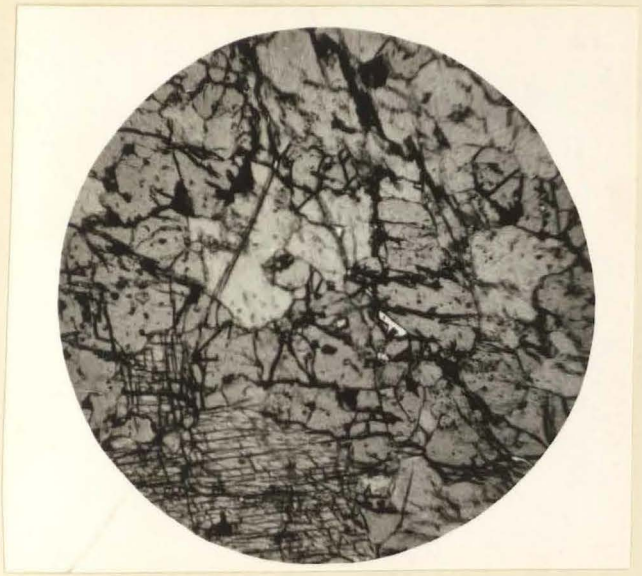


Plate LXV. Rhodonite and garnet in pegmatite.
Rhodonite (Rh) showing well developed cleavage is present with garnet (Gr) and felspar.
(Plane Polarized; x 30).



Plate LXVI. As Plate LXV.
(Crossed Nicols; x 30).

As the temperatures decreased unmixing of the unstable minerals took place.

Subsequently supergene enrichment occurred to a limited extent. The effects of this enrichment was to

replace garnet, rhodonite and even felspars by manganese dioxides. The hausmannite lamellae also suffered replacement, and in extreme cases even jacobsite was altered to peroxides. The addition of silica during the dryer periods unfortunately offset most of the beneficial effects in the top few inches of ore.

Although a paragenetic chart cannot be constructed for these metamorphic manganese minerals in the same way as for hydrothermal ore types, a table relating the minerals to the periods of metamorphism, pegmatitic action, temperature decline and supergene alteration is nevertheless instructive. Where, during the period of metamorphism, more definite relationships can be deduced from textures of the ores, the data is included. (See Table XIX).

TABLE XIX.

PARAGENETIC SEQUENCE OF ORES.

Mineral	Period of Metamorphism	Pegmatitic Period	Period of decreasing temperature	Period of supergene Effects
Braunite	———	———	—	
Hollandite	———		—	
Garnet	———	———		
Jacobsite	———			
Rhodonite	———	———		
Ba Felspars	——			
Hausmannite	——		———	
Vredenburgite			———	
Bixbyite	—			
Chalcophanite	—			
Haematite	———	———		———
Mn. Pyroxenes		———		
Pyrolusite				———
Psilomelane				———
Silica				———

5. Deduced Origin of the Primary Manganese Ores.

As an aid to further prospecting, as well as from the academic viewpoint, it is important to re-construct the depositional history of the manganese beds and itabirites in detail. In arriving at the conclusion that the manganese mineralisation was syngenetic and that subsequent metamorphism accounts for the formation of the high temperature suite of minerals, the following factors are relevant:

1. The manganese ore-bodies lie in definite stratigraphic horizons within metamorphosed sediments.
2. The manganese ores are intimately associated with the itabirites which are known to be of sedimentary origin.
3. The ore makes sharp contacts against the quartzites, and no transgressive relationships exist.
4. The granitic rocks postdate the mineralization.
5. Relict banding, both on the macro- and micro-scale, can be recognized.
6. The general absence of replacement textures in the ores underlines the mode of origin.
7. Such gangue minerals as barium-felspars and garnets are present as metacrysts.
8. The absorbed trace elements, viz. barium, boron, calcium, cobalt, lead, magnesium, zinc and tin, are, with the exception of the last, typical of manganese sediments.

Four important problems are set by the sedimentary origin of these manganese deposits, viz. the source of the material, the form in which the manganese existed in solution, the form in which it was deposited, and finally the separation of this element from others. Each of the

problems will be discussed in turn.

(1) The source of the manganese: For large tonnages of manganese to be accumulated in a sedimentary deposit, two sources could provide the material: either older deposits which were also rich in manganese, or rocks in which manganese was present in small quantity. Unlike many of the Indian deposits, no rocks other than those studied have been noted to contain large proportions of manganese from which the younger deposits could have derived. It is thus probable that the deposits represent concentrations of the formerly dispersed manganese present in therocks undergoing weathering.

(2) The form in which manganese existed in solution: Unlike the problem of source material, there is an abundance of evidence that the manganese existed in solution as the bicarbonate. Trace element determinations of the ores detected lead, zinc, cobalt, calcium, barium, magnesium, and tin. Rankama and Sahama (1949) state that barium, calcium, lead, cobalt and magnesium all move as bicarbonates. They further state that nickel preponderates over cobalt in hydrolyzates, but in oxidates the reverse is noted. Zinc moves as the sulphate or chloride, but is often absorbed to a considerable extent by oxidate sediments. The only trace element which is not soluble to any extent is tin; however, it has been found and reported by Goldschmidt and Peters (1933) in sedimentary iron ores up to a value of 8 grams/ton. Its presence in the manganese ores may, however, be due to pegmatitic action.

During weathering manganese is dissolved as the bicarbonate $Mn(HCO_3)$. In the case of iron, when oxygen is absent, ferrous iron is readily dissolved in water containing carbon dioxide to form ferrous bicarbonate. In carbonate-bearing waters the Mn:Fe ratio is often 5:1.

(3) The form in which manganese was precipitated: The decomposition of the bicarbonate leads to the formation of Mn^{4+} compounds, and this element, together with iron, first forms hydroxides which loose their water rapidly to become the stable peroxide MnO_2. On loss of carbon dioxide from the waters ferrous carbonate is precipitated. This ferrous carbonate in turn is unstable in the presence of atmospheric and dissolved oxygen and becomes oxidized to ferric compounds. Furthermore, ferrous bicarbonate may be decomposed into ferric hydroxide and carbon dioxide by organic agencies. Ferric iron does not form a bicarbonate.

(4) Separation of manganese from iron: In the south-eastern portion of the Windhoek district Gevers (1934) noted that manganese is virtually absent from the itabirites; however, up to 11% Mn is present in the northern occurrences (verbal communication by Dr. Martin). It is therefore certain that the manganese and iron had a common source and were precipitated under similar conditions; yet a definite separation into manganese-rich and manganese-poor beds took place. This is partly due to the greater affinity of iron for oxygen, with the result that iron is more readily oxidized and precipitated as ferric hydroxide than the comparable manganese hydroxide. On the other hand, ferric hydroxide is a weak base, whereas manganic hydroxide is weakly acidic. A mixture of the two hydrosols flocculate one another, but when there is an excess of one of the sols the less abundant sol is recharged.

The operation of these factors must now be judged on the basis of field evidence. A paper by Borchert (1953) on marine iron ores indicates the conditions under which leaching, solution and reprecipitation of iron takes place. Borchert states that extensive iron ore deposits are not

derived from leaching of continental rocks, but newly transported and deposited detritus is leached within the depositional basin in "carbonate zones" ("Kohlensaure-Zonen"), which form where organic material is not freely attacked by oxygen. Such a condition is known to have existed during the deposition of the limestones in the Otjosondu area as witnessed by the present of graphite flakes and sulphidic gases in the marbles. In these "carbonate zones" reduction and solution of iron and manganese took place. Jeppe (1952) found that the percentage of iron in amphiboles increased from the oldest to the youngest throughout a profile of hundreds of feet of rocks of the Damara System. He concluded that this was due to changes during metamorphism, but leaching of iron throughout the profile may also account for the variation.

Deposition of iron and manganese is known to take place under oxidizing conditions, and the Otjosondu occurrence is no exception, for it is within the coarse clastic members of the sedimentary cycle that the ores are found. In the Kaokoveld the sedimentary iron ores, always occur in the tillite zone of the Marble Series, either above or below it, occasionally even replacing it. This indicates that the climate was probably frigid. Leaching, and deposition due to oxidation variation in rhythm with the seasons is suggested in the South West African deposits, for in winter deposition of iron and manganese would occur, whereas in the summer leaching would be promoted, and although some of the quartz present in the ores was precipitated from solution, clastic material must have been added during the winter, thus accounting for the rhythmic banding of both manganese and iron ores.

The whole concentration of elements in the water must have been changing with time, for instances have been noted where the top assay, of a borehole is rich in

manganese whereas the bottom is manganese poor, an instance being given in Table XX. An important sidelight on this

TABLE XX.

ASSAY VALUES ACROSS ORE BODY IN BOREHOLE L.R. 1/738.

(140 ft. to 160 ft. giving 20 ft. ore).

Sample Taken	Mn(%)	Fe(%)
Near Upper Contact	51.7	6.4
144 ft.	51.1	6.1
148 ft.	51.4	6.2
152 ft.	46.3	5.4
156 ft.	46.9	7.3
Near Lower Contact	26.6	17.1

fact is that, if this relationship can be proved to hold for all bodies, then a method is available for finding top and bottom of ore horizons at depth by reference to a detailed assay plan.

CHAPTER III.

GEOPHYSICAL METHODS OF PROSPECTING.

Little geophysical work was under taken by the author, but the present prospecting scheme is using magnetometric methods to trace the suboutcrop of the itabirites beneath the sandcover. The magnetic intensity of the itabirites is somewhat higher than the country rocks, and with the knowledge that the manganese ores follow the itabirite horizon, drilling is facilitated.

The manganese ores are themselves magnetic due to the presence of jacobsite; however, since the bodies are relatively narrow and steeply inclined, they are apt to be missed on regional ground traverses. Furthermore, when the ore is highly magnetic grade is low, and although such bodies will prove the trends of ore, nevertheless they are economically valueless.

The electromagnetic method of testing the extent and continuation of ore beneath the sand has not yet been used, but it is considered worthy of trial. Experiments conducted at the Geological Survey indicate that the conductivity of ore is extremely high when compared with that of the itabirites and quartzites. This method should provide valuable data which could be used in advance of mining to determine structures, thickness of ore and length of strike.

CHAPTER IV.

CONCLUSION.

It is considered that as the mining of Manganese proceeds in the area geological guidance will become more and more important, and that the field will continue to produce manganese for a considerable period, thereby proving an asset to the expanding economy of South West Africa.

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