THE MONAZITE DEPOSITS OF THE VANRHYNSDORP DIVISION, CAPE PROVINCE

by

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PRETORIA.
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Plate I.- Monazite ore enclosing xenoliths of altered wall-rock. Steenkampskraal. x 1.5.

This study is dedicated
to those who believed,
and were patient.

Who hath measured the waters in the hollow of
his hand, and meted out heaven with the span,
and comprehended the dust of the earth in a
measure, and weighed the mountains in scales,
and the hills in a balance?

Isaiah 40: 12.

CONTENTS

Page

LIST OF ILLUSTRATIONS

TEXT FIGURES

Figure | Page

PLATES

MAPS (in pocket)

THE MONAZITE DEPOSITS OF THE VANRHYNSDORP DIVISION

CAPE PROVINCE

Abstract

Monazite occurs with apatite, zircon, iron and copper minerals in hydrothermal lodes in the Archaean Complex. The mineralisation appears to be related to structural features and hydrothermal alteration of a porphyroblastic granite-gneiss. There are three primary and two placer occurrences. Except for monazite, which exhibits the rare phenomenon of polysynthetic twinning parallel to the basal pinacoid, the ore-minerals are normal in all their properties.

Geographically, the occurrences are near the southern extremities of the Kamiesberge where they disappear beneath the Knersvlakte peneplane, leaving an inselberg topography controlled by the semi-arid climate. Geologically the area is one in which the Archaean basement has been exposed through the removal of overlying Nama and younger sedimentary formations, some of which remain as outliers.

The Archaean rocks, because they present certain features which are inconsistent with the intrusion of primary granites into metamorphic rocks, are believed to have formed by regional granitisation of the Malmesbury Formation.

The truncation of one ore-body by the pre-Nama erosion surface indicates a pre-Nama age for the mineralisation, and placer deposits of monazite and zircon have been located in the Nama sediments.

Controls have been established to guide the search for further primary occurrences of radioactive minerals, and suggestions are made accordingly for the continued survey of the area.

I.- Introduction

(i) General. Monazite, which is a thorium-bearing phosphate of cerium and related rare-earth metals, is a common accessory mineral in syenitic and granitic rocks. It is also found in gneisses and schists of related composition, and generally attains its best development in pegmatites associated with these rock-types. It is seldom recovered from the primary occurrences, however, being generally very sparsely present in them. When the parent rock is broken down by weathering, the monazite, which is resistant, becomes concentrated as a detrital mineral. It therefore features prominently in certain beach-sands, river alluvials and hill-slope eluvial deposits in localities where monazite-rich rocks are suitably disposed for the mineral to be concentrated. It may be recovered in its own right, or as a by-product of workings for ilmenite, rutile, cassiterite or columbite.

Prior to production from Steenkampskraal, where the largest deposit in the Vanrhynsdorp Division is situated, the major world sources of monazite were from beach-sands in Travancore (India), in Espirito Santo and Bahia (Brazil), and in New South Wales and Queensland (Australia). Small supplies were obtained from placers in Idaho, North Carolina, Florida, Indonesia, Malaya, Ceylon, Nigeria, Egypt, Norway and elsewhere. Attention has lately been focussed on recently discovered monazite-, ilmenite- and zircon-bearing beach-sands near the mouth of the Mandrare River and in the Fort Dauphine area, Madagascar. Davidson (1956, pp. 197-208) and the Mineral Information Bureau, Geological Survey of India (Anon., 1954, pp. 297-303) give an adequate review of the localities, history, economics and figures for monazite production up to 1956, and the reader is referred to these publications for further details. Davidson describes the Steenkampskraal deposit as bed-rock ore, in contrast to the common placer or beach-sand occurrence. It is interesting to note from his paper that the only other bed-rock source of monazite which has ever been exploited is at Shelby in North Carolina, where a granitised gneiss containing about 0.5% monazite was crushed to enable the mineral to be extracted. This venture was, however, a failure.

The monazite deposits of the Vanrhynsdorp Division, being in the form of epigenetic lodes, are therefore of a type hitherto thought to be unique among world occurrences. Davidson (1956, p. 205), however, mentions that similar occurrences have recently been reported from the Mojave desert of California. Monazite has also been reported from "...a typical vein-type hydrothermal deposit, associated with pitchblende, gold and sulphide..." at the Shinkolobwe Mine in the Belgian Congo (Traill, 1954, p. 6). Unfortunately, descriptions of either of these occurrences are not yet available.

Granular monazite and apatite of similar dimensions to the Vanrhynsdorp material have lately been reported from the Fort Dauphine area. They differ from the Vanrhynsdorp minerals, however, in that they occur in pegmatites. These are transgressive to the Archaean Complex and may be related to pegmatite mineralisation in the Union (Besairie, 1957, p. 129). Metasomatically introduced monazite in this country has been recorded by Mendelssohn and Marland (1933, pp. 113-115) for the Main Reef Leader in the Sub Nigel Mine. This mineralisation apparently preceded the alteration of the country-rock, which is the reverse of the sequence of events in the area under discussion. The authigenic nature of the monazite is confirmed by Liebenberg (1955, p. 159) who examined the mineral in polished section (1955, Plate VIII, Fig. 10). Irregular bodies of intimately associated apatite and monazite near Bandolier Kop in the Zoutpansberg District have been ascribed by Janisch (1926, pp. 109-135) to pneumatolytic action connected with the emplacement of granitic pegmatites in basic gneiss.

The Vanrhynsdorp ore carries a variable but generally high percentage of monazite, and the value of the deposits is enhanced by the fact that the ore can be recovered by standard mining methods and the monazite easily separated by flotation.

(ii) Scope of the Investigation. The detailed investigation carried out by the author in the Vanrhynsdorp Division was two-fold in purpose. Firstly, a hitherto unknown type of monazite occurrence had to be investigated; secondly, the surrounding area had to be examined so that controls for the mineralisation could be established, and used if possible to locate further deposits of radioactive minerals.

The work began in 1950 with the investigation of the only deposit then known, on Steenkampskraal. This was followed by a reconnaissance survey over part of the area covered by Map 2 viz. north, north-west and west of Steenkampskraal. The geological formations to the east and south which are not obscured by sand are represented by Nama sediments, in which, at that time, radioactive minerals were considered unlikely to occur.

In 1952 new deposits were reported from Roodewal and Uilklip; these were investigated firstly by Dr. John de Villiers of the Geological Survey Office (1953), and later by the present author. The deposits are similar in nature to the one on Steenkampskraal.

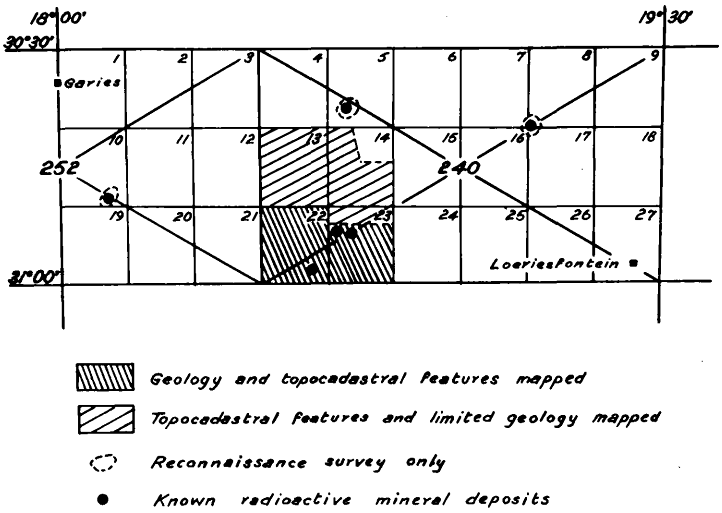

Fig. 1.- Locality plan of field-work done in relation to positions of deposits. Diagram shows numbers of 10-minute field-sheets comprising Geological Sheet 240 and part of Geological Sheet 252.

The map resulting from the original reconnaissance survey proved to be insufficiently detailed, and the whole 10-minute field-sheet (no. 22 in Fig. 1) was accordingly re-surveyed in 1954. Adjoining field-sheets were covered in 1955, after which the investigation was stopped.

This report contains the findings of the investigation as a whole.

(iii) Previous Work. Of the early workers in the western and north-western Cape Province, only Rogers has paid attention to the immediate area in which monazite mineralisation has taken place, in surveys conducted during 1900, 1904 and 1911, but no reference is made to this mineralisation in his reports (1901, 1905, 1912). Subsequent to the

Plate II.- Panoramic view of the mine and quarters on Steenkampskraal, looking from the ore-bearing koppie south-eastwards over the Knersvlakte to the Escarpment in the distance, and southwards to Meulsteenberg. On the extreme left are the inclined shaft and the ore-dressing plant, and immediately to the right of them is the power plant. The married and single quarters are on the right of the photograph.

(Photo by C.A. Gibson)

discovery of the deposits, mapping by officers of the Geological Survey was extended northwards to the 31st parallel, which just touches the southern boundary of Steenkampskraal. Apart from this, earlier mapping of part of the Archaean Complex west of Vanrhynsdorp had been done by Lamont (1947), and Brink (1950) mapped aspects of the Complex and overlying sediments in the Nuwerus area west of longitude 18°30'.

The only available geological map covering the mineralised area at the time this investigation commenced, therefore, was that of Rogers. It served as a valuable basis for localising different formations and structures, and was therefore of considerable assistance in the planning of the field-work.

(iv) Location of the Deposits. The primary deposits occur on the farms Steenkampskraal, Roodewal and Uilklip, and the detrital deposits that have so far been located are on Uilklip and Leeuw Kuil (see Maps 1, 2 and 3).

The main deposit is on Steenkampskraal, 50 miles NNE. of Vanrhynsdorp by road, and is situated some three-quarters of a mile due north of the Meulsteenberg trigonometrical beacon, near the boundary with Brandewynskraal.

The other deposits form a group on the aforementioned farms which adjoin each other 9 miles NNE. of Steenkampskraal. The primary deposits in this area are situated in the south-west and south-east corners of Roodewal and Uilklip respectively, and the detrital deposits due east and west of these respectively.

All the deposits are easily accessible, being near to the secondary road between Vanrhynsdorp and Kliprand.

II.- Regional Geology

A. Physiography

The area is characterised by inselberg topography, in which the remnants of the Kamiesberg ranges digitate southwards and ultimately disappear beneath Recent deposits which cover the peneplane known locally as the Knersvlakte (see Plate II). The ranges of hills trend NNW.- SSE., and are generally capped by outliers of resistant Kuibis sediments. Where these cappings have been removed by erosion, high ground is formed by somewhat less resistant meta-quartzite, which is especially prominent in the west central part of the area. In general, the ranges have gentler slopes to the west than to the east, as a direct result of the protection offered by the cappings of westward dipping Kuibis sediments (see Plate III).

The low ground in the area has probably been caused by sub-aerial peneplanation of deposits which choked valleys during Recent times. The level of the drowned topography corresponds to that of actual peneplanation of the Nama System south of this area, and it is suggested that upwarping of the coast-line has given rise to the inland choking of the river-valleys.

A rejuvenated, dendritic river-system is, however, at present incising the meanders in the old river-courses, and thereby reducing the level of peneplanation by depths of up to 50 feet. This rejuvenated drainage may be related to the Recent fall in sea-level described by Krige (1947). The drainage is largely influenced by the geological structure, in that the large streams flow in the troughs parallel to the NNW.- SSE. fold-axes, and the tributaries drain the dip-slopes westward or take advantage of structural weakness to cut right through the ridges (see sections on Map 2). Where rivers cross the Nama System, or Nama rocks overlain by Recent deposits, they tend to migrate towards the shale or towards the Recent deposits, as these are more easily eroded than the quartzite. The drainage leaves the area in a south-westerly direction and feeds the Geelbeks River.

As the area receives less than 5 inches of rain per annum, the rivers only flow after heavy downpours, and the vegetation is typically that of a semi-arid region, being largely represented by succulents and hardy, stunted shrubs.

B. Geological Formations

Gravel, clay, sand, gypsum, calcrete etc.			RECENT DEPOSITS
---------------- Angular unconformity ----------------			
Silcrete			TERTIARY SYSTEM ?
---------------- Angular unconformity ----------------			
Quartz veins			
Dolerite			
Limestone, calcareous shale, shale, flagstone, grit, arkose, conglomerate		Schwarzkalk Series	NAMA SYSTEM
Conglomerate, arkose, feldspathic sandstone, sandstone, feldspathic quartzite, quartzite, micaceous shale		Kuibis Series	
-------------------- Nonconformity --------------------			
Lodes of monazite ore, magnetite, barite			
Quartz veins			
Pegmatite			
Mafic granulite group*	Metasediments	Probable granitised equivalents of the MALMESBURY FORMATION	ARCHAEAN COMPLEX
Metaquartzite group			
Aplogranite group			
Pyroxenite	Palingenetic or metamorphic differentiates		
Anorthosite			
Porphyroblastic granite-gneiss			

The regional distribution of the Archaean Complex and the overlying sedimentary formations as tabulated above, is shown in Map 1.

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* The word "group" is used to embrace related rock-types which differ slightly due to gradational changes in composition. Their uncertain position in the stratigraphical sequence and limited distribution do not warrant the use of a term such as "suite" or "formation" (cf. use by Tyrrell, 1946, p. 136).

C. Description of Formations

1. Archaean Complex

The Archaean Complex is represented by metamorphic rocks which can be correlated with the Malmesbury Formation, and by the so-called Namaqualand granite-gneiss, the rôle of which is still a subject of some debate.

The term "Namaqualand granite-gneiss" has been used in the past by different authors to indicate both porphyroblastic and aplo-types of granite-gneiss, as distinct from the clearly metamorphic rocks (Brink, 1950, p. 149; de Villiers, 1950; Gevers, Partridge and Joubert, 1937, p. 29; Lamont, 1947; Mathias, 1940). Detailed field-work by the present author and others has shown, however, that the aplo-types are most likely highly granitised arenaceous rocks, and they have therefore been grouped with the Malmesbury granulites and metaquartzites (Jansen, 1955: 1956, p. 3; Lamont, 1947).

The porphyroblastic granite-gneiss underlies the metamorphic and granitised rocks throughout the area. It may be considered to be a granite intrusive into the overlying rocks, and contaminated by them, but it more likely represents highly granitised lower members of the Malmesbury Formation. These would normally underlie the recognisable sedimentary correlatives that occur south of this area.

(a) The Malmesbury Formation

Field- and petrographical study of the metamorphic and granitised rocks in the area suggests that they were originally sedimentary in nature, and they can indeed be traced westwards through Bitterfontein and then southwards to the Moedverloren Hills to indisputably sedimentary rocks of the Malmesbury Formation, passing into the latter through decreasing grades of metamorphism (Jansen, 1955: 1956, pp. 2-4). The metasediments, as the metamorphic rocks have therefore been termed, have been subdivided by the present author as shown in the following Table.

Table No. 1.- Metasediments of the Malmesbury Formation

Mafic granulite group	Magnetite-garnet-biotite granulite, biotite schist, biotite-hypersthene granulite, sillimanite-cordierite gneiss
Metaquartzite group	Metaquartzite, feldspathic metaquartzite, recrystallised quartz veins, quartz "blows"
Aplogranite group	Aplogneiss, aplogranite, interfoliated aplite and pegmatite
Palingenetic or metamorphic differentiates	Pyroxenite and anorthosite

The three groups are listed in stratigraphical sequence, with the granulite group occurring either at the top of the succession, or lenticularly within the metaquartzite near the top of the succession. The pyroxenite and anorthosite, which occur as ill-defined bodies in the porphyroblastic granite-gneiss, have been tentatively assigned to the metasediments as possible palingenetic or metamorphic differentiates, the formation of which followed the processes of regional granitisation.

Many variants of the three groups occur because of gradational variation in the proportions of the constituent minerals; for the purpose of mapping, however, one group comprising chiefly metaquartzites was distinguished from another consisting of dark-coloured granulites, gneisses and schists, and both of these groups were distinguished from the more granitoid aplogneisses and aplogranites. The metaquartzite and granulite groups represent metamorphic products of essentially different composition and occupy different positions in the local stratigraphical column. All the constituent rock-types are gneissose to variable degrees.

The contacts between the various rock-types of each group, and between the groups themselves, are gradational. The passage from any group to the granite-gneisses is likewise gradational, and all the contacts are generally parallel to the foliation-planes* in the granite-gneisses

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* All the structural and directional features of the crystalline rocks in the area are described in the terms used by Balk (1937).

Plate IV.- Lit-par-lit injection contact between aplogranite (light-coloured) and granulite (dark coloured) on the boundary between Banken and Klein Banken.

and the metasediments. Banded and lit-par-lit injection contacts are common (see Plate IV).

A vertical section of the contact between porphyroblastic granite-gneiss and granulite is exposed in the middle of Bushmans Graaf Water. Here the foliation of one is parallel to that of the other, the feature being the more emphasised by the development of parallel bands of biotite schist, biotite aplite and pink aplogranite in the porphyroblastic granite-gneiss a few feet away from the granulite.

In the metasediments which form the range of hills in the west of the area, however, the foliation, if extrapolated from any point well up in the succession towards the granite-gneiss contact, would be cut by it. Mobilisation of the metasediments must therefore have taken place at the present contact with the granite-gneisses, in order to present the ubiquitous parallel directional features referred to already.

Lit-par-lit injection contacts between granulite and aplogranite are striking on Bushmans Graaf Water and Klein Banken. Transgressive dykes of aplite cut the foliation, but have undergone deformation in the plastic country-rock and have been ptygmatically folded.

(i) The Mafic Granulite Group. The mafic granulites are medium- to coarse-grained and equigranular to seriate rocks. They are dark in colour and weather dark-brown or black. In general, they seem to be more resistant to weathering than the surrounding granite-gneiss, and they form slightly higher ground. Their type occurrence is in the west of the area where they are associated with metaquartzite. In the eastern and north-eastern parts of the area the metasediments are entirely represented by mafic granulite.

The granulites consist of the following minerals in variable proportions:- plagioclase (andesine to labradorite), potash feldspar, hypersthene, biotite, almandine (identification by Brink, 1950, p. 128), cordierite, sillimanite, quartz, the ore-minerals magnetite, ilmenite and occasionally pyrite, and accessory apatite and zircon.

Biotite and hypersthene appear to be the oldest minerals and are often highly altered. They are interstitial to, and appear to be replaced by the feldspars, which sometimes partially enclose them (18998, 19677[*]). The hypersthene has an optic axial angle $2V_\alpha = 64°$[✱] and therefore contains 26% $FeSiO_3$ (Kennedy, 1947).

Potash feldspar is most often represented by microperthite. The plagioclase blebs are of the string, rod and less often, of the bead type described by Alling (1938, pp. 142-165). The microperthite frequently displays turbidity about these blebs (18999). Plagioclase is saussuritised, giving rise in extreme cases to distinct grains of epidote and chlorite (19002, 19009; similar to Plates XV, XXXV and XXXVI). The plagioclase occasionally shows compound twinning i.e. two sets of polysynthetic twins in the same crystal with composition-planes at right angles to one another (19010, 19682). This feature has been observed in thin sections cut from almost every type of crystalline rock in the area, and reference to migration curves for plagioclase (Emmons, 1943, p. 152) shows the combinations to be of two types <u>viz</u>. albite-pericline and Manebach-Ala.

Quartz, by virtue of recrystallisation, is striking in its interstitial character. It is associated with the alteration of the mafic minerals to chlorite and epidote (18998, 19010), forms symplektite with orthoclase[⊕] (19001), and itself encloses zones of secondary micas.

Associated with the quartz are ilmenite, magnetite (sometimes partially altered and replaced by pyrite : 18998), garnet and apatite. The apatite and quartz apparently replace feldspar. Magnetite encloses or replaces older minerals, strikingly so in the case of sillimanite and cordierite (19681: cf. Brink, 1950, pp. 129-133). Grains of zircon frequently replace biotite. The garnet is intimately associated with the quartz.

The gradational contacts between the granite-gneisses and the granulite are represented by migmatites,

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[*] Geological Survey Office serial numbers of thin sections.

[✱] The Universal Microscope Stage was used as far as possible for all the petrographic measurements and identifications, following the procedures described by Emmons (1943).

[⊕] Not to be confused with myrmekitic replacement of cordierite by quartz (Brink, 1950, pp. 131-132). For this orthoclase, $2V_\alpha = \pm 70°$, increasing with more pronounced alteration.

and have been indicated on Map 2 as dashed lines. These migmatites are represented by greater concentrations of mafic minerals in the granite-gneisses, generally in bands or with well-defined directional features. Similar features are encountered along the contacts between granulite and metaquartzite. Granulite appears to form where the mafic minerals increase in proportion, and the plagioclase increases both in proportion and An-content at the expense of the granite-gneiss minerals. It is extremely difficult to make generalisations regarding the manner in which the constituent minerals vary in concentration, but the typical gradational change in composition from granite-gneiss to granulite is very well illustrated in a small occurrence of granulite resembling a pendant on Tafelberg Remainder.

Here the granulite is almost entirely surrounded by aplogranite; in the latter, bands of almandine are present, and these give way as biotite and other mafic minerals increase in proportion. The granulite rock in the centre of the occurrence is represented by labradorite, biotite, hypersthene, quartz, apatite and ore-minerals, in order of decreasing percentage. Thin sections cut at intervals over the gradational contact (18999-19003) reveal that the banding is due to alternating zones of quartz, garnet and opaque ore-minerals (19000). Biotite tends to be replaced by magnetite and ilmenite (19000), and is often altered to chlorite (19002) or sagenitic chlorite (18999), or to limonite and leucoxene (19000, 19002). In the aplogranite, microperthite is dominant over plagioclase, but passing into granulite, the plagioclase increases in proportion and in An-content from An_{30} to An_{63}, potash feldspar disappearing altogether.

In a small occurrence of granulite near the middle of Tafelberg Extension No. 1, the feldspar is also represented entirely by andesine of composition An_{43-46} (18998). Both antiperthite and perthite are present in migmatites on Tafelberg Remainder (19679). Plagioclase with the greatest An-content observed (An_{70}) occurs in a biotite-hypersthene schlieren on Riet Kloof. This plagioclase forms more than two-thirds of the feldspar present, the rest being represented by orthoclase.

The contact between granulite and granite-gneiss is occasionally sharp, and biotite so concentrated that bands of biotite schist a few feet thick represent the granulite group, as is the case on Bushmans Graaf Water, Vlermuis Gat and Riet Kloof. Garnet is coarsely developed in the granulites which are interfoliated with the metaquartzite on Klein Banken; hand-specimens and thin sections of these rocks have been described in great detail by Brink (1950, p. 127). Unfortunately, they appear to have been taken over a restricted area, since the cordierite and sillimanite which this author regards as so characteristic of the occurrence, are not as ubiquitous as his thesis would suggest. These two minerals do, however, occur in considerable quantities in the contact-zones, often to the exclusion of plagioclase (Brink, 1950, p. 128). They have also been encountered by the present author in well-lineated, banded granulite forming contact-zones on Riet Kloof in the extreme north (19681) and on Leeuw Kuil in the extreme east of the area. The cordierite is often altered to pinite.

The granite-gneisses seem to be characteristically pink near the contact-zones. On Bushmans Graaf Water the aplogranite is dark red and contains recrystallised quartz. In the north-west corner of Steenkampskraal the contact is typically banded. Parallel veins of pink aplogranite occur in granulite composed of biotite, garnet, red feldspar and quartz; the aplogranite in turn contains bands of magnetite and biotite, and a thin band of magnetite less than an inch wide occurs in the granulite. The banding in the latter rock diminishes away from the contact as the proportion of garnet decreases and the colour of the rock darkens. Also on Steenkampskraal, east of this occurrence, biotite schist grades into biotite granulite which is in contact with pink aplogranite. The core from a diamond-drill hole into the unweathered rock shows that the aplogranite changes colour to the normal grey a few feet away from the contact. Tongues of leucocratic pegmatite, which weather pink at the surface, penetrate the metasediments and the aplogranite parallel to the foliation-planes.

On the boundary between Riet Kloof and Puts, a dark, nodular rock occurs in the granulites near the homestead; its appearance is suggestive of a metaconglomerate. In thin section (19683) the nodules consist of biotite-hypersthene aggregates containing labradorite (An_{52}), a little potash feldspar, quartz and apatite, set in a schistose, biotite-rich ground-mass.

Biotite schist is composed mainly of biotite and quartz (19668). Unusually large quantities of apatite are present, together with a little feldspar and magnetite. All these minerals clearly replace the biotite. Throughout the area, magnetite and biotite are titaniferous (confirmed by hydrogen peroxide wet tests); both biotite and its secondary alteration product chlorite may contain sagenitic webs, and extreme alteration of biotite and magnetite yields leucoxene (19001).

Brink (1950, pp. 112, 136) has preferred to call all these rock-types, irrespective of structure, texture or composition, high-grade hornfelses, resulting from the thermal metamorphism of "...certain shaly material acted upon by the noritic rocks of pre-granitic age...". As such they may possibly be assigned to types 2 and 4 of the Goldschmidt Classification (Harker, 1952, p. 97). The mineral assemblage, however, is not quite characteristic of common hornfels, the most marked difference being the abundance of biotite and almandine, especially in the contact-zones. Furthermore, the gradations in composition, the banding at contacts, the presence of injected aplitic or pegmatitic material, the equigranularity of the rock-types, the grain-size and fabric suggest an origin other than mere thermal metamorphism.

Almandine is usually associated with conditions of regional metamorphism (Harker, 1952, pp. 219-224) where stress and high temperatures prevail. Cordierite and sillimanite are likewise high-temperature minerals, but are associated with conditions of no stress (Harker, 1952, pp. 227-232). The combination of these three minerals, however, together with biotite, potash feldspar, hypersthene and plagioclase is typical of Grubenmann's Katazone of metamorphic rocks, or Barrow's sillimanite zone (Turner and Verhoogen, 1951, pp. 416-418). By reason of the field- and petrographical evidence, therefore, the rocks under discussion have been termed granulites (cf. Williams, Turner and Gilbert, 1955, pp. 229-231, 235-238), and would fall into groups 1 and 2 of Eskola's granulite facies (Turner and Verhoogen, 1951, p. 474). Rogers (1912, p. 26) has also preferred to term these rocks granulites. The composition of the hypersthene-bearing types is essentially charnockitic, and the metamorphic nature of the environment strongly suggests analogous conditions of formation to those quoted by Barth (1952, pp. 232-233).

Taking all the field- and petrographical evidence into account, the nature of the metamorphism which gave rise to the granulites may be tentatively summed up as follows:-

1. The alteration of biotite and hypersthene and the replacement of these minerals by all the others suggets their early formation from argillaceous material. They are essentially relict minerals represent~~e~~ing an opening phase of thermal metamorphism. Subsequent to their formation, temperature and pressure increased.
2. Katazonal metamorphism gave rise to the formation of almandine while stress prevailed, and at a later stage when stress diminished, to sillimanite and cordierite.
3. The feldspars became increasingly enriched in soda and potash away from the granulite; the fact that no zoned crystals are present indicates that equilibrium was established.
4. Any free silica present was rendered mobile and then recrystallised.
5. The rock as a whole was rendered sufficiently mobile for the minerals to adapt themselves to stress conditions and thus form well-defined planes of schistosity. This mobilisation has been more intense in the contact-zones, where the foliation of the granulites has been developed parallel to that of the underlying metasediments or granite-gneisses. The mobilisation is further betrayed by ptygmatic folding of transgressive aplite veins.
6. Release of pressure and lowering of temperature closed the cycle. Almandine possibly became unstable and dissociated to form magnetite and spinel rimmed by sillimanite (Brink, 1950, p. 133). In a thin section (19681) cut from a highly lineated cordierite-sillimanite gneiss occurring on Riet Kloof, however, magnetite encloses perfect crystal forms of sillimanite, and replaces cordierite; the sillimanite-magnetite relationship seems therefore more likely to be one of replacement than one of alteration from garnet.

(ii) The Metaquartzite Group. The metaquartzite occurs in the west and south-west of the area, generally forming high ground. To the north removal of these rocks by erosion has exposed the underlying granite-gneisses; to the east and west they are overlain by Nama and Recent formations.

The metaquartzite tends to strike ENE.- WSW., deviating locally where tightly folded, pitching structures occur. Most dips are steep, and the presence of bodies of mylonite parallel to the limbs of folds on Klein Banken and Tafelberg Remainder suggests that the formation has not only undergone folding but has ruptured as well. The mylonites are *en echelon* in distribution, up to 12 feet in width, and consist of aggregates of quartz, sericite, epidote and chlorite. Streaks of limonite-stained leucoxene remain from primary ore-minerals. Fresh magnetite and ilmenite are associated with younger quartz, and together with small needles of sillimanite which are developed parallel to the strike of the shear-zones, replace the mylonitic groundmass (19685, 19686). Zircon also replaces the mylonite in sufficient quantities to provide a higher radiometric normal than that of the country-rock.

Reconstruction of the pre-Nama peneplane from the position of present-day Nama outliers indicates a vertical thickness of at least 800 feet for the metaquartzite on Banken and Tafelberg Extension No. 1 (see Map 2, sections 2 and 4). Apart from the granulites, associated types of metasediment, which are represented only by boulders and pebbles in the Schwarzkalk conglomerates, also indicate that the metasediments were originally thicker and more extensive than they are at present.

The stratigraphical position of the metaquartzite relative to the granite-gneiss on the one hand and the granulite on the other is shown in the occurrences on Vlermuis Gat and Brandewynskraal (see Map 2). The farm beacon stands on a round hill composed of granulite overlying metaquartzite roughly in the form of an anticline pitching west, the southern limb of which is in turn overlain by metaquartzite; granulite therefore occurs here between an upper and a lower succession of metaquartzite. Elsewhere, however, the relationship is not so distinct, as the members of either the granulite group or the metaquartzite group may be absent or only lenticularly developed.

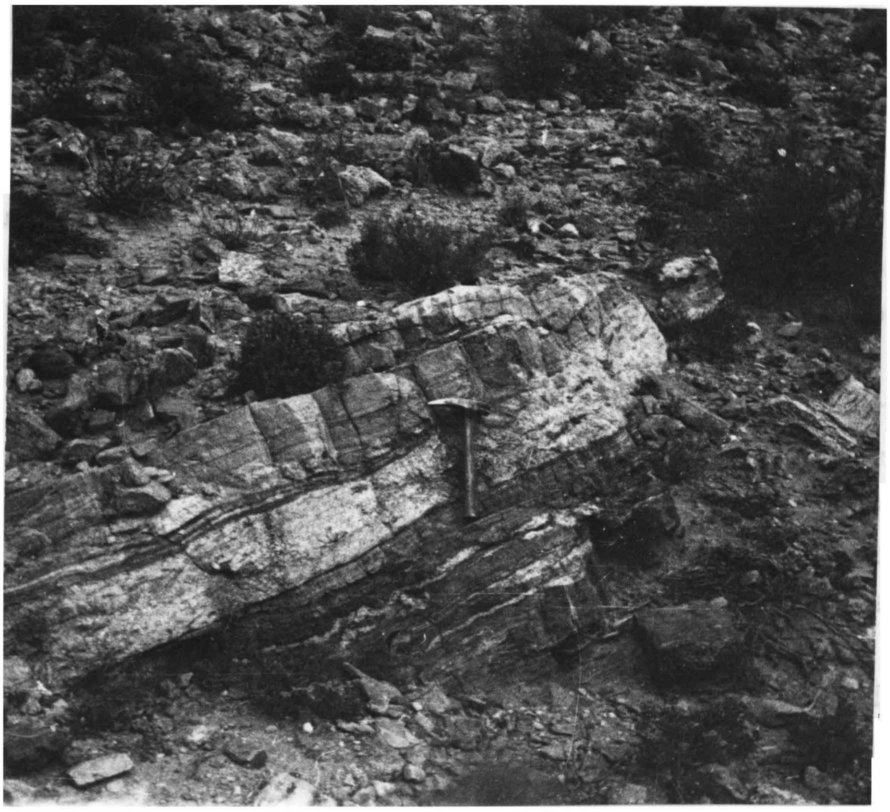

Plate V.- Parallel bands of pegmatite (light-coloured) in metaquartzite (dark-coloured) near the contact with porphyroblastic granite-gneiss on the boundary between Brandewynskraal and Vlermuisgat.

The nature of the contact between the metaquartzite and the granite-gneisses varies. Where the former is in contact with aplogranite, the contact is gradational over a considerable distance. The contact with the porphyroblastic granite-gneiss to the south, however, is sharper, and the metaquartzite contains bands of magnetite, biotite and garnet; veins of pegmatite parallel to the contact occur a few feet away from it in the metaquartzite, and are seen to advantage on Vlermuis Gat (Plate V). The anticlinal structure is apparently truncated near the crest by porphyroblastic granite-gneiss, which is now exposed in the core of the anticline. The foliation-planes of the metaquartzite are, however, parallel to those of the granite-gneiss in the contact-zones.

The contact between metaquartzite and granulite is gradational. On Brandewynskraal, for example, the succession from metaquartzite downwards to granulite passes through metaquartzite containing parallel bands of coarsely garnetiferous, aplitic to pegmatitic material and biotite-granulite schlieren, followed by biotite schist which developes into granulite containing more interfoliated aplitic to pegmatitic material. This interfoliated material, and the associated aplogranites, are often pink in colour, especially where the contact is contorted. Pegmatites transgressive to the foliation and which are therefore likely to be younger in age, also occur along the contacts; magnetite is common in both the interfoliated and the transgressive types.

Segregations and disseminations of coarsely crystalline magnetite occur at the contact on Vlermuis Gat, Banken and Leeudans; some of these occurrences run to hundreds of pounds over a small area (see Maps 2 and 3).

The composition of the metaquartzite varies from nearly pure quartzite to very feldspathic quartzite containing variable amounts of magnetite, garnet, sericite, epidote, biotite and chlorite. Quartz concentrations of variable size and form are fairly common; the quartz is sometimes colourless or milky, but is more often a conspicuously dark, bluish colour due to the presence in it of finely disseminated ferruginous material. A few of the occurrences are vein-like and have merely become recrystallised; the rest are more indefinite in form, resembling blows, and may represent highly siliceous differentiates. All the bodies are sheared and recrystallised to different degrees. A recrystallised quartz vein of this type which contains monazite and xenotime in small amount, was found on the farm Kobeeb, about 25 miles north of these occurrences (see position of deposit marked on Map 1, and in field-sheet 5, Fig. 1).

The metaquartzites are fine- to medium-grained and granulose, often highly recrystallised. In thin section (19005-19007, 19678) they are allotriomorphic granular, comprising an equigranular aggregate of quartz and feldspar. Microcline is present in great excess of orthoclase and plagioclase. The feldspars are usually altered to sericite, epidote, chlorite etc., especially along the edges of the grains where they are truncated, rounded and replaced by quartz. The relationship is very distinct and precludes the possibility of any of the feldspars having developed from a micaceous matrix in the original sediment. Metaquartzite near the contact with granite-gneiss (19676) contains fresh microperthite which apparently replaces the common altered feldspars. The microperthite is of the film type illustrated and described by Gates (1953, pp. 58-59, Plate 6) and may have originated as this author suggests through structural control and replacement (p. 61) and not exsolution. Fresh quartz may have been added, but the fabric is more characteristic of recrystallised quartz already existing in the sediment. Between crossed nicols some sections show recrystallisation in individual grains, some show strain shadows in both quartz and feldspar, but the rest show neither. Quartz sometimes forms vermicular intergrowths with altered orthoclase and aggregates of chlorite (19674).

The orientation of c-axes in a banded metaquartzite near the contact with porphyroblastic granite-gneiss on Brandewynskraal was measured according to the method described by Haff (1938, pp. 543-574). The diagram (see Fig. 2, p. 19) shows that the quartz has not crystallised with the c-axes exactly parallel to the foliation-plane (a-b) or perpendicular to the strike of the foliation (b-b). According to Bloss (1954, p. 1355) quartz tends to fracture along planes parallel to the rhombohedral face. The discrepancy (a-a') of 26° in the present analysis approximates somewhat to the angle of 38° between the c-axis and any rhombohedral face, and suggests that this principle has been operative in the reconstitution of the quartz in this metaquartzite.

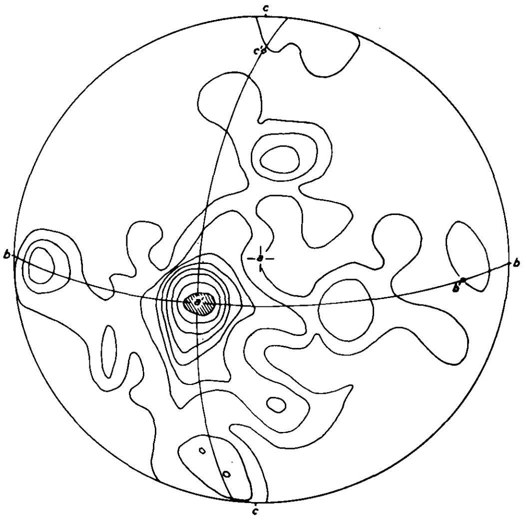

Fig. 2.- Petrofabric diagram of 320 quartz axes in metaquartzite from Brandewynskraal (19005). Contour intervals in per cent: >7-6-5-4-3-2-1-0. Fabric axes as determined in the field, a, b, c; as determined by point maxima, a', b', c'.

Epidote often occurs in zones and veins along the contacts and in some transgressive pegmatites. A thin section (19008) shows it to be present as a felt of fine-grained laths in quartz, associated with altered feldspar.

The metaquartzite is usually very resistant to weathering and forms conspicuously high ground. To the west of Hoedkop, however, weathering has penetrated this rock very deeply, and it is represented only by a quartz-clay aggregate, stained along former joint-planes by secondary ferruginous matter. The quartz from weathered metaquartzite has probably contributed largely to the building of the arenaceous members of the overlying Nama formations.

The metaquartzite, according to Brink (1950, p. 149), represents "...very pure original sandstone or grit with a small amount of feldspathic material..." which has undergone moderate regional metamorphism by what this author regards as an intrusive Namaqualand granite. The metaquartzite is, however, clearly associated with the granulites, which have been shown by the present author to be products of high-grade metamorphism. Furthermore, part of the metaquartzite succession occurs between granulite and granite-gneiss, and would therefore be expected to show an even higher grade of metamorphism than the granulite group. Summarising the most important field- and petrographical information, the following features indicate that the grades of metamorphism responsible for the formation of the granulites were also operative for the metaquartzites:-

1. tightly folded, steeply dipping, sometimes ruptured, strata;
2. gradational contacts between metaquartzite and aplogranite;
3. mobilisation of material at contacts, and parallelism of foliation in contact-zones between metaquartzite and both granite-gneisses;
4. recrystallisation throughout the metaquartzites;
5. mobilisation of recrystallised quartz, and presence of vermicular and symplektitic intergrowths;
6. alteration of pre-existing feldspars;
7. presence of bands of magnetite and garnet;
8. presence of perthite younger than common altered feldspar.

(iii) The Aplogranite Group. The aplogranite or aplogneiss is a grey to light-pink, fine- to medium-grained rock, generally aplitic, rarely porphyroblastic in nature. Its texture is usually granulose, but is occasionally granophyric, and the rock then becomes dark red in colour. The composition is granitic.

It usually occurs stratigraphically between members of the granulite group or the metaquartzite group, and the porphyroblastic granite-gneiss, but may be absent from this position, as for instance on Vlermuis Gat and Brandewynskraal, where the porphyroblastic granite-gneiss is in direct contact with both metaquartzite and granulite.

The upper contact of the aplogranite with the metasediments is clearly gradational. The lower contact with the porphyroblastic granite-gneiss may be either gradational or comparatively sharp. Where it is sharp, the aplogranite is interfoliated with the porphyroblastic granite-gneiss as tongues, lenticles or sill-like bodies. Several of the latter transgress the dip of the foliation-planes of the porphyroblastic granite-gneiss, remaining, however, parallel to the strike. Since the margins of these transgressive bodies do not truncate or disturb the growth of the minerals in the country-rock (see Fig. 3, p. 21), the aplogranite cannot be of younger age, and must therefore represent "ghosts" (granitised xenoliths) of formations

Plate VI.- Schlieren of metaquartzite assuming the composition of aplogranite. Shows tendency to conform to the direction of foliation of porphyroblastic granite-gneiss indicated by handle of prospecting pick. Near the bottom of the plate, a pegmatite vein cuts a granulite schlieren which has already been oriented to correspond with the direction of foliation in the granite-gneiss. Uilklip.

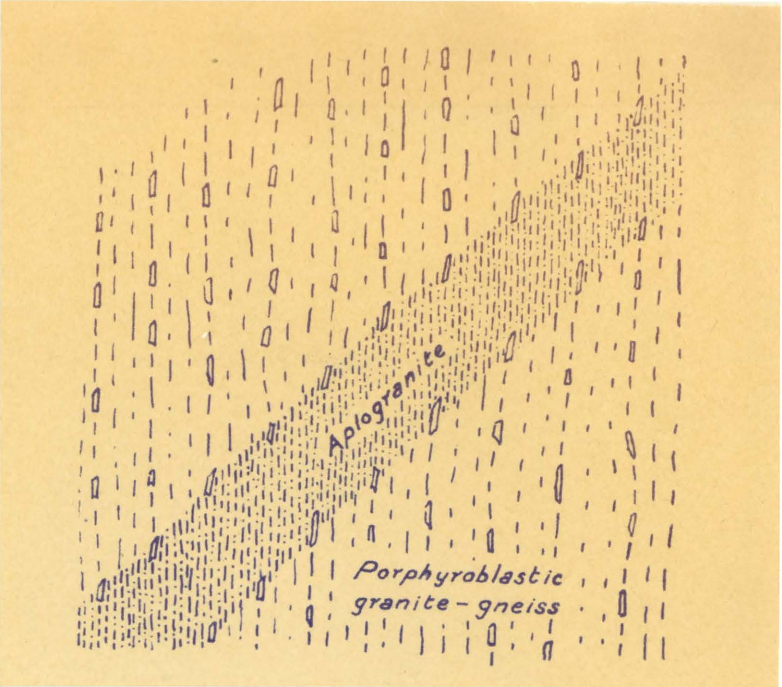

Fig. 3.- Diagrammatic representation of aplogranite "ghost" in porphyroblastic granite-gneiss. The longest axis of the aplogranite lies transverse to the dip of the porphyroblastic granite-gneiss foliation. Although the contact between the two rock-types is well defined, it does not limit the growth of the country-rock minerals.

older than the porphyroblastic granite-gneiss. The transgressive attitude of these bodies to the foliation of the country-rock indicates that they were not sufficiently mobilised to assume the directional features of the surrounding granite-gneiss. These "ghosts" occur locally on Brandewynskraal and Bushmans Graaf Water. The interfoliated bodies may be regarded as granitised xenoliths which did become sufficiently mobilised to attain correct orientation, since their directional features correspond exactly with those of the porphyroblastic granite-gneiss (see Plate VI). The contacts of these bodies are not sharp enough for them to be regarded as palingenetic material injected into the main mass of rock, or for that matter, true aplites.

The foliation and lineation in the aplogranite is provided by the orientation of quartz, feldspar and mafic minerals, and small porphyroblasts of potash feldspar wherever they are developed. Where the directional features are prominent, the term aplogneiss is applicable. The rock is always leucocratic, being composed mainly of feldspars and quartz; varying quantities of magnetite, ilmenite, garnet and biotite are present, and if the latter mineral is

Plate VII.- Bands of aplogranite (light colours) containing clots of garnet (dark), interfoliated in porphyroblastic granite-gneiss on Steenkampskraal.

altered to chlorite, the rock becomes faintly mottled. The aplogranite on Steenkampskraal and Bushmans Graaf Water often has large clots of garnet, sometimes exceeding an inch in diameter, developed in it (Plate VII). Flinty, dull green porphyroblasts sometimes occur in the aplogranite at its contact with metaquartzite, and probably represent feldspar crystals partially altered to epidote. On Roode Kloof the alteration of locally coarser-grained aplogranite at the metaquartzite contact is particularly prominent. The age of this alteration post-dates the emplacement of the pegmatites.

To the north of the area on Riet Kloof, Tafelberg Remainder etc., lineation in the aplogneiss is strongly brought out by garnet, biotite and/or magnetite. Flow-layers dip steeply, and are overfolded, laminated or contorted, suggesting the action of compressive forces. Where contacts are exposed between aplogneiss, porphyroblastic granite-gneiss and granulite, they are very irregular as a result of mobilisation, but the general east-west trend in directional features is still discernible. Occasionally, where the aplogranite is massively developed, the foliation is difficult to trace. Bands of aplite containing coarse garnet crystals cut the directional features of the aplogranite and displace them locally, suggesting emplacement while the country-rock was still plastic. These aplite bands are especially common at depth in the succession, and contain much magnetite and garnet where they cut dark-coloured bodies of granulite.

Brink (1950, pp. 154-164) has already dealt with the petrography of "the Namaqualand Granite" in great detail, and although this author has made no genetic distinction between the porphyroblastic and aplo-types, his description of the essential properties of the constituent minerals is adequate for either type. The present author has in general, therefore, confined his description of the minerals of both the porphyroblastic and the aplogranite-gneisses, to features which have some bearing on their origin.

In thin section, potash feldspar predominates over plagioclase, and quartz varies in percentage. Present in variable quantities are garnet, biotite, ilmenite, magnetite and accessory apatite and zircon. A sample near the granulite contact on Klein Banken contains a little cordierite (18995).

The potash feldspar is usually microperthite. The blebs of plagioclase are of the string, rod and less often, of the bead type described by Alling (1938, pp. 142-165), and the enclosing feldspar either orthoclase or untwinned microcline (19675). The microperthite encloses plagioclase, apatite and zircon, and is itself replaced by vermicular intergrowths of quartz. It is usually somewhat sericitised, the alteration proceeding from the exsolution plagioclase and inclusions. Unaltered grains of orthoclase and untwinned microcline (cf. Strauss, 1942, p. 40) are present as well (19675, 18994-18996).

The plagioclase is usually oligoclase, more or less constant in composition (An_{27-32}). A little antiperthite (19673) is also present. The plagioclase sometimes shows the compound twinning described under the granulites.

The mutual relationships between the feldspars suggest that the first to form was probably plagioclase; the composition of later feldspars becomes progressively richer in soda and potash content, through antiperthite to microperthite, microcline and orthoclase.

Biotite is a dark-brown variety but is usually altered to chlorite and, when replaced by magnetite and ilmenite, to limonite as well. Some grains contain sagenite (cf. Mathias, 1940). The magnetite and ilmenite occur separately or mutually intergrown, and associated with quartz. Garnet occurs in subhedral to euhedral grains, associated with quartz. Zircon and apatite are widely disseminated, occurring interstitially to other minerals, or enclosed by feldspar or biotite. They also appear to be associated with quartz.

Quartz is the youngest mineral by virtue of recrystallisation, and it has truncated or replaced all the older minerals. Grains show undulose extinction or recrystallisation shadows between crossed nicols. The striking association of quartz with the ore-minerals, garnet, apatite and zircon would suggest their introduction contemporaneously with its recrystallisation and mobilisation.

The microscope shows pink granophyric granite to be brecciated and recrystallised aplogranite (18997); the recrystallisation of the quartz is especially pronounced. The feldspars and biotite are generally altered and are replaced by quartz. Euhedral accessory minerals, particularly apatite, are abundantly present.

The aplogranite-gneiss is considered to have originated from the metasediments by granitisation, and in the field this is borne out mainly by the gradational passage from one to the other.

The change from granulite to aplogranite has already been discussed in the section dealing with the granulites. Jansen (1955) has distinguished between biotite-rich and biotite-free aplogranites in the Moedverloren and Bitterfontein areas, but the present author has attempted no such subdivision in this area. Jansen maintains that biotite-rich aplogranite has originated from a biotite paragneiss; the presence of much biotite in the aplogranite of this area is probably indicative of origin from granulite, which may or may not correspond to the required biotite paragneiss. Conversely, the absence of biotite is most likely indicative of origin from metaquartzite, although biotite and other micas already occur in the latter.

In the case of the metaquartzite, the passage to aplogranite seems to be characterised by more intense recrystallisation and the metasomatic addition of feldspar. In the following table, typical metaquartzite is compared petrographically with typical aplogranite.

Table No. 2.- Petrographical comparison of metaquartzite and aplogranite

	Metaquartzite	Aplogranite
Composition	Quartz, sericitised microcline, orthoclase and plagioclase.	Microperthite, quartz and plagioclase.
Fabric	Allotriomorphic, granulose.	Granitoid, granulose.
Quartz	Recrystallised, replaces altered feldspars with formation of some symplektite.	Recrystallised, replacing all other minerals.
Feldspar	Predominantly microcline; a little orthoclase and plagioclase. All highly altered.	K-feldspar mostly microperthite enclosing plagioclase. Some orthoclase and microcline present. Sericitisation about exsolution blebs only.

In the contact-zones between aplogranite and granulite the plagioclase becomes progressively richer in soda and potash content towards the aplogranite. Such a change is more difficult to trace between aplogranite and metaquartzite, because the latter already contains much

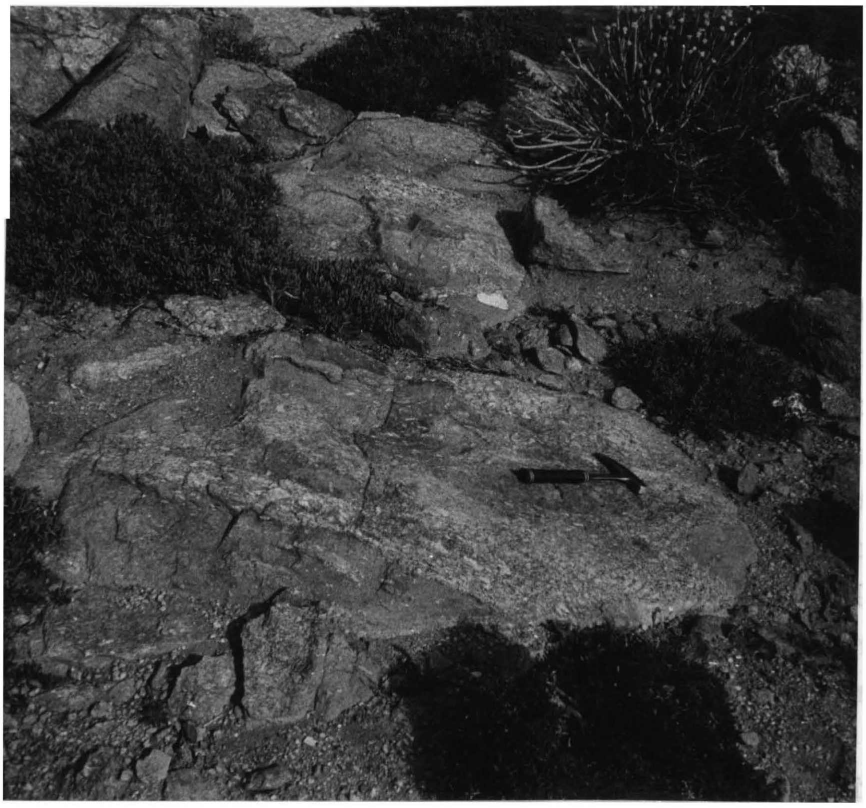

Plate VIII.- Porphyroblasts developed in dark-coloured schlieren surrounded by porphyroblastic granite-gneiss on Uilklip. Note growth of coarse porphyroblasts in schlieren near handle of prospecting pick.

Plate IX.- Aplogranite on Uilklip representing granitised metaquartzite which occurs to the east. The near-horizontal foliation is indicated by flow-layers of garnet.

original feldspar. Furthermore, quartzite or sandstone is relatively inactive under any conditions of regional metamorphism (cf. Reynolds, 1946, pp. 409-413). In the aplogranite itself, however, early-formed plagioclase seems to be replaced by younger microperthite as mentioned in the section dealing with petrography.

In the north-west corner of Uilklip a pendant of metaquartzite occurs in the porphyroblastic granite-gneiss (see Map 2). The metaquartzite is highly garnetiferous and contains many small bodies of dark-coloured granulite, in which large porphyroblasts of feldspar are developed (see Plate VIII). The metaquartzite is eroded away to the west, but if the line of strike is followed WNW. across the stream-bed, an aplogranite is encountered which at first is texturally very similar to the metaquartzite, then becomes leucocratic, highly recrystallised, compact and foliated farther west (Plate IX). In a thin section cut from the metaquartzite (19676) most of the feldspar is represented by extremely fine film perthite. In one cut from the aplogranite (19675), the feldspar is largely microperthite replacing orthoclase. The plagioclase blebs in this case are of the string and rod variety.

In a thin section cut from the contact-zone between aplogranite and metaquartzite on Klein Banken (19674) fresh microperthite also replaces altered feldspar.

Lamont (1947), comparing the average chemical compositions of the "Pink Gneiss" (this author's term for aplogneiss), the Namaqualand Grey Gneiss and the Older Basement granite-granodiorite, came to the conclusion that the "Pink Gneiss" largely represents a potash-enriched product of granitisation. The evidence may be summarised as follows:-

1. Chemical evidence:-

	Average K_2O/Na_2O ratio	$\%K_2O$
"Pink Gneiss"	1.75	5.24
Grey Gneiss	1.61	5.02
Granite-granodiorite	1.43	3.76

2. Mineralogical evidence:-

Elongation ratios of zircon grains plotted on a frequency diagram display a maximum about a ratio of ±1.7, which is characteristic of original sedimentary rocks, whereas the ratios for igneous rocks tend to form maxima between 1.9 and 2.3.

The granitisation process from metaquartzite to aplogranite in this area may therefore be tentatively summed up as follows:-

1. Recrystallisation of the quartz and reconstitution of the altered feldspar took place beyond the grade required for the formation of metaquartzite.
2. Symplektitic intergrowth took place between orthoclase and quartz.
3. Metasomatic enrichment in alkalies was represented by the formation of fresh oligoclase, which was replaced in turn by more potash-rich feldspars, the whole eventually represented by microperthite.

(iv) Pyroxenite and Anorthosite. Small bodies of pyroxenite and anorthosite a few feet long and wide occur interfoliated in the porphyroblastic granite-gneiss. The two main constituent minerals are hypersthene and andesine, the one occurring in great excess of the other, thereby giving rise to either rock-type.

Pyroxenite occurs on Roodewal and Uilklip in stunted bodies resembling dykes. The rock is black except where coarse growths of andesine are present.

In thin section (19645, 19646) large, irregular grains of plagioclase replace an equigranular pyroxene ground-mass. The minerals are subhedral to euhedral. Pyroxene grains reach 2 mm. in diameter; the ore-minerals are generally less than 1 mm. in size.

Hypersthene forms 95% of the thin sections examined except where plagioclase is present in excess. It has characteristic optical properties. N_γ varies from 1.709 to 1.721, indicating a variation in $FeSiO_3$-content from 34% to 42% (Kennedy, 1947).

No potash feldspar is present. Plagioclase of composition An_{50} replaces and sometimes encloses grains of hypersthene. Compound twinning according to the albite and pericline laws was observed.

Accessory apatite, occurring interstitially in euhedral grains, magnetite, pyrite and chalcopyrite are present. The magnetite is partially altered and replaced by pyrite, which in turn is replaced by chalcopyrite. A little primary biotite is present, showing alteration and partial replacement by magnetite.

Six small occurrences of anorthosite, also but a few feet wide and long, were found in the area covered by Map 2, on Bushmans Graaf Water, Tafelberg Extension No. 2, Uilklip, Riet Kloof and Kruispad. The contacts in each case are not clearly exposed, but occurrences to the east of this area are clearly interfoliated.

The rock may be light or dark in colour, but is characteristically free from quartz and contains over 85% of andesine. The bodies show no directional features or preference for any particular form, apart from a faint horizontal foliation in the Uilklip occurrence. An aureole of altered granite a few feet wide, characterised by pink feldspar, much chlorite and veins of epidote, usually surrounds each occurrence. On Uilklip, recrystallisation of quartz has taken place in the country-rock. On Kruispad the chlorite seems to have been derived from the alteration of the hypersthene. The overlying Kuibis sediments are conspicuously coloured by red feldspar and green epidote and chlorite, and there can be no doubt, therefore, that the anorthosite is pre-Nama in age. On Riet Kloof, the association of anorthosite with chloritic breccias and altered granite is fortuitous in that it occurs near a pre-Nama fault-zone.

In thin section (19648-19651) the anorthosite is equigranular to seriate and has a granitoid texture. All the mineral grains are anhedral except apatite; the feldspar grains are present in all sizes up to 7 mm. in diameter whereas the pyroxene is equigranular and only reaches 1 mm. by comparison.

Andesine (An_{37-47}) forms at least 85% of the rock, the remainder being represented by hypersthene and its alteration products, and a small percentage of accessories. The plagioclase is sometimes twinned according to the Carlsbad B law, but compound twins according to the albite and pericline laws are common. It appears to be younger than the pyroxene, sometimes enclosing it ophitically. Untwinned grains are generally antiperthitic; the optic axial angle for the exsolution mineral is $2V_\alpha = \pm 70°$. The andesine is slightly saussuritised, but its exsolution blebs are clear, which suggests that they might be soda-orthoclase.

The unaltered hypersthene has characteristic optical properties. $2V_\alpha$ varies from 46° to 60°, indicating an $FeSiO_3$-content varying from 42% to 29% (Kennedy, 1947). In all the sections examined, the hypersthene shows varying degrees of alteration, firstly to fibrous biotite and then to chlorite. The alteration proceeds along fractures and cleavages in the pyroxene from outer rims in contact with andesine.

Primary biotite is highly altered to chlorite and no longer retains its original outline. Secondary biotite, recrystallised from altered hypersthene, stands out markedly from the fibrous variety and the primary biotite.

Accessory minerals are apatite, magnetite and pyrite, all of which replace the minerals already mentioned. Apatite grains are small, euhedral and well disseminated, and are frequently found in feldspar. Rounded grains of magnetite sometimes replace biotite, but are otherwise well disseminated; pyrite occurs in small grains associated with the hypersthene.

The origin of the pyroxenite and anorthosite cannot be established with certainty, because the bodies lack the essential criteria of structure and well-defined contacts. Features of the Complex such as the parallelism of schistosity- and foliation-planes along the contacts between metasediments and granite-gneisses, lit-par-lit injection contacts, banded contacts, contorted contacts, and ptygmatically folded aplite veins, have been referred to in the foregoing pages. They all point to mobilisation and re-injection of the Complex following the processes of granitisation, and it is considered from their mineralogical composition that the pyroxenite and anorthosite represent extreme palingenetic or metamorphic differentiation products formed during this stage. If they are of the latter origin, they are probably of the secretion type described by Barth (1952, pp. 317-318). The age relationship and composition of the pyroxene and plagioclase are similar to those of the granulites, and the three rock-types may therefore be genetically related. The pyroxenite and anorthosite occur only in portions of the porphyroblastic granite-gneiss some distance away from any contact with metasediments, and this may indicate that they have formed *in situ*. On the other hand, if the alteration aureoles often associated with the anorthosite are taken into account, the bodies may have been re-injected into the mobile Complex just prior to consolidation.

Plate X.- Porphyroblastic granite-gneiss containing porphyroblasts of potash feldspar in flow-layers dipping away from the observer, on Steenkampskraal.

Plate XI.- Dark-red fringes to joints in porphyroblastic granite-gneiss on Bushmans Graaf Water.

(b) The Porphyroblastic Granite-gneiss

This granite-gneiss derives its name from the distinctive presence in it of large porphyroblasts of potash feldspar. They are especially conspicuous when the granite-gneiss is well foliated (see Plate X), but are often rather haphazard in orientation, and the directional features of the granite must then be sought in the finer-grained minerals of the ground-mass. As such, they are provided by quartz-feldspar bands, sometimes alternating with zones of darker minerals. Lineation is provided in the main by the orientation of quartz grains.

When fresh, the rock is grey in colour; it weathers light brown, and is characteristically pink to dark red where affected by hydrothermal action. At levels near the re-exposed pre-Nama peneplane, joints and fractures in the granite-gneiss have dark-red fringes (see Plate XI). This is not a very common feature, and the alteration might be attributed to the action of circulating ground-water during the deposition of the Nama sediments. This alteration, combined with the effects of extreme jointing and partial recrystallisation during the post-Nama tectonics, has occasionally served to obliterate the directional features of the granite-gneiss. One example of this is the granite exposed in the core of an anticline on Riet Kloof.

The porphyroblastic granite-gneiss is exposed by the erosion of overlying sediments and metasediments, and tends to occur most frequently in the south and west of the area.

The overall composition of this granite-gneiss remains very constant throughout the area (cf. Brink, 1950, p. 154) but locally, the composition may vary greatly. This is borne out by differences in analyses (Brink, 1950, p. 168). The porphyroblasts are of microperthite, and are set in a ground-mass of more microperthite, microcline, orthoclase, oligoclase and quartz (see Plate XII facing next page). Highly variable quantities of biotite, almandine, magnetite, ilmenite and accessory apatite and zircon are present. Grains of monazite have been observed in heavy mineral residues from granites with radiometric normals higher than the average. Concentrations of almandine, as in the aplogranite, are seldom found, but biotite and magnetite may become very concentrated locally.

That the porphyroblastic granite-gneiss is not of truly magmatic origin is suggested mainly by its

Plate XII.- Potash feldspar porphyroblasts separating biotitic flow-layers in porphyroblastic granite-gneiss, Steenkampskraal. Scale in inches.

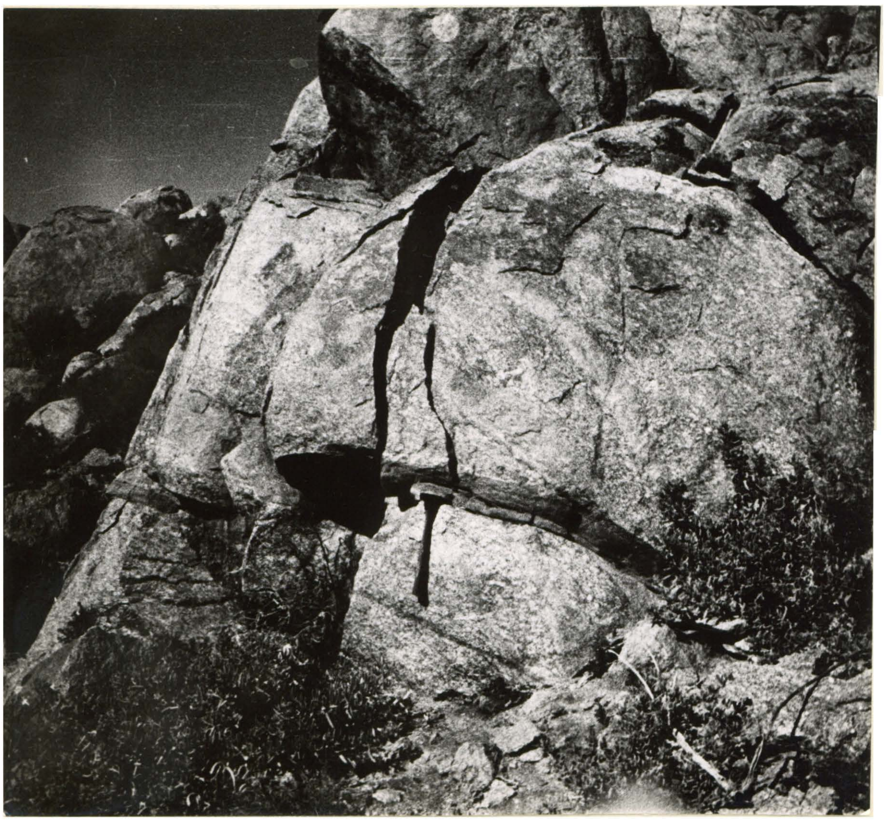

Plate XIII.- Narrow bands of biotite granulite (dark-coloured) cutting the foliation of porphyroblastic granite-gneiss on Steenkampskraal.

transitional relationship to the metasediments and to the schlieren they form in it, by "ghost structures", by its potash-rich porphyroblastic nature, and by local variations in accessory mineral content in itself.

Schlieren occurring in the porphyroblastic granite-gneiss near its contact with metasediments are generally well defined. Like the aplogranite they may be interfoliated or transgressive to the foliation, appearing in the latter case as "ghost structures" . Leucocratic schlieren show the transition from metaquartzite to aplogranite, often containing much garnet (see Plate VI); the melanocratic types may show the growth of potash feldspar porphyroblasts in them (Plate VIII) with concentrations of garnet at their margins, and the transition to granulite from the centre outwards. They may form veins and dykes of the type encountered on Steenkampskraal and Uilklip through mobilisation (Plate XIII). The fact that schlieren are seldom found except in association with the metasediments, and then only as highly granitised features, suggests that they have become indistinguishable from the granite-gneiss with increase in distance from the contact.

In thin section the granite is inequigranular, seriate to porphyroblastic, the porphyroblasts being represented by subhedral to euhedral microperthite. They may reach a length of 10 cms. but are usually of the order of 3 to 5 cms., set in a much finer-grained ground-mass, the texture and composition of which resemble those of the aplogranite. Grain-size in the ground-mass is usually less than 5 mm., if quartz is disregarded; recrystallisation of this mineral has given rise to anhedral aggregates of greatly variable proportions and dimensions.

Potash feldspar is represented by both microperthite and orthoclase. Microperthite forms all the porphyroblasts and most of the potash feldspar in the ground-mass, and is easily distinguished by the sericitisation proceeding from its inclusions and exsolution lamellae (see Plates XIV and XV). It encloses plagioclase, orthoclase, zircon, apatite and magnetite, and is replaced by quartz, with which it forms linear to sub-linear, vermicular, symplektitic intergrowths; these intergrowth replacements are also sericitised. Carlsbad twinning in the microperthite is prominent.

Orthoclase occurs mainly in the ground-mass, truncating and replacing older minerals. It is not perthitic and is sericitised only about the edges of its grains.

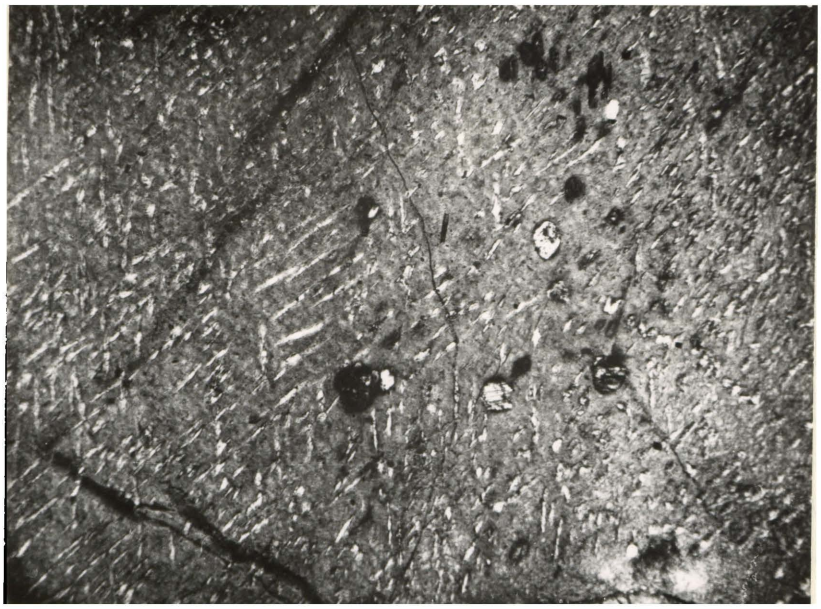

Plate XIV.- Microperthite showing exsolution along crystallographic directions, and enclosing plagioclase (round, white grains, one of which is polysynthetically twinned) and apatite (dark, euhedral prisms). Crossed nicols. x 32. 17945, Steenkampskraal.

Plate XV.- Incipient sericitisation of microperthite in areas of turbidity about the planes of exsolution. Crossed nicols. x 100. 17945, Steenkampskraal.

It encloses euhedral magnetite with no signs of expansion cracks, and could therefore post-date the formation of the magnetite (17945). The orthoclase usually displays undulose extinction. A few of the grains have small optic axial angles of $2V_{\alpha} = 54° - 60°$ (17945); these were also observed by Brink (1950, p. 155).

Microcline, despite the prominence given it by Brink (1950, pp. 154-155), was not observed in any of the thin sections studied; this is possibly because this author regards "...porphyritic texture.....(as) exceptional..." , and his description of the granites is mainly that of the aplo-types, in which microcline does occur. Jansen (1955) has also noted the occurrence of microcline in the aplo-types, but does not refer to it in his description of the porphyroblastic types of granite-gneiss. Rogers (1912, p. 26) was the first to identify microperthite forming both "...porphyritic crystals..." and part of the matrix.

Plagioclase generally forms a small percentage by comparison with the potash feldspar, but is dominant over it in instances where the granite is very biotitic (18992). This is a feature typical of the granodiorite described by Strauss (1942, pp. 37-38) from the Springbok area, and by Jansen (1955) from the Moedverloren and Bitterfontein areas. Antiperthite was also observed occasionally. The plagioclase is generally oligoclase, but andesine of composition up to An_{43} has been measured. Saussuritisation of the plagioclase is often marked, with the rare accompaniment of sericitisation as well. It forms symplektite with younger quartz in the same way as orthoclase.

Biotite is generally a dark-brown variety, but some green biotite is present. Muscovite may be developed in biotitic granite as well. The biotite would appear to be the oldest mineral, being replaced by all the others. Association with quartz has resulted in its alteration to dark-green chlorite exhibiting anomalous interference colours; limonite and leucoxene have been formed along the cleavage-planes. The chlorite displays some affinity for replacement by magnetite and ilmenite. The association of biotitic granite with argillaceous members of pre-gneiss rocks is discussed by Strauss (1942, pp. 42-44) and has already been referred to by the present author.

The ore-minerals are magnetite and ilmenite, usually emplaced interstitially in rounded grains, and they seem to be associated with quartz and zircon. Alteration has given rise to the usual secondary products.

Quartz, through recrystallisation and mobilisation, replaces all the other minerals. Between crossed nicols its aggregates show recrystallisation shadows which may be directional to some extent, and individual grains occasionally show undulose extinction. The quartz-feldspar symplektite usually occurs along the margins of the feldspar crystals (18990, 19664-19666) and it is not clear whether it replaces the feldspar or is replaced by it. The symplektite is never enclosed by the feldspar, however, but is usually a partial rim between the latter and the quartz, which suggests that its formation post-dates that of the feldspar.

Almandine seems to be associated with quartz, and both these minerals replace altered biotite. The serrated outlines of the garnet suggest some replacement by quartz.

Accessory minerals are apatite and zircon, and these also appear to be associated with quartz. Zircon displays an affinity for magnetite and the replacement of biotite, and is often enclosed by quartz, whereas prisms and needles of apatite are only prominent as inclusions in feldspar. The apatite is clearly slightly older than the quartz.

Two narrow, *en echelon* veins of lamprophyre a few feet long occur in the porphyroblastic granite-gneiss on Vlermuis Gat and in aplogranite on Banken. In thin section (19647) laths of labradorite (An_{58}) and xenoliths of fibrous and spherulitic chlorite are enclosed in a pilotaxitic ground-mass of labradorite needles, a mineral altered to chlorite and ore (pyroxene ?), and very finely divided, dark-coloured ore.

The study of thin sections has indicated clearly the growth of microperthite porphyroblasts in this granite-gneiss, replacing earlier-formed plagioclase and orthoclase in the ground-mass. The relationship between potash feldspar and plagioclase, described in the section dealing with the transition from granulite to aplogranite, also holds good here, biotite-rich granite containing more plagioclase than potash feldspar. It is therefore natural to infer that enrichment in potash has taken place.

In the field, the limit of development of these porphyroblasts is the contact of this granite-gneiss with the aplogranite, metaquartzite and granulite. Up to the present, only the transition from metaquartzite or granulite to aplogranite has been considered; now the porphyroblastic granite-gneiss is found in contact not only with the aplogranite, but also in direct contact with metaquartzite and granulite, no intervening aplogranite being present. Since these contacts are largely gradational, it is natural to infer that the contact represents a "front" of granitisation characterised by a visible enrichment in potash, as evidenced by the growth of the porphyroblasts (cf. Reynolds, 1946, pp. 409-415: 1947, p. 108). In keeping with Jansen's findings in the Moedverloren and Bitterfontein areas (1955: 1956, p. 5), this "front" characterises a second phase of granitisation, and does not necessarily conform to the previous one by which aplogranite was formed.

Rogers (1905, pp. 19-29: 1912, pp. 18-30), Gevers, Partridge and Joubert (1937, pp. 28-34), Brink (1950, pp. 106, 150), de Villiers (1950) and du Toit (1954, pp. 56-58) have all regarded the emplacement of the granites in the Complex as being due to normal cycles of batholithic intrusion associated with orogenesis. Coetzee (1941, p.196) supports these authors in the main, but mentions granitisation as the probable origin of granite in the Springbok area after measuring the length-breadth ratios of the zircon (1941, pp. 191-193). Lamont (1947, pp. 15, 68, 83) states quite definitely that the "Pink Gneiss" of the Moedverloren area (aplogneiss) represents highly granitised sediments, which this author, like Brink, at that time correlated with the Kheis System. Read (1951, p. 20) regards these granites as conforming largely to the autochtenous section of his Granite Series, or Plutonic Association (1944, p. 93). No doubt the intrusive relationships of different granites described by some of the afore-mentioned authors north of the area under discussion, correspond to the parautochtenous and plutonic sections of this author's Granite Series as well.

The features which have been regarded by the present author as criteria for granitisation, are the following:-

1. Transition in composition from porphyroblastic granite-gneiss to metasediments.
2. Transition in composition of schlieren enclosed by the porphyroblastic granite-gneiss, from metaquartzite to aplogranite, and from melanocratic migmatite to granulite.
3. Presence of "ghost structures" of aplogranite transgressive to the foliation of the porphyroblastic granite-gneiss.
4. Distinct feldspathisation of melanocratic schlieren.

5. Local concentrations of garnet (cf. du Toit, 1954, p. 62) and ore-minerals.
6. Petrographic evidence of enrichment in potash feldspar, and replacement of pre-existing minerals by porphyroblasts of microperthite.
7. Petrographic evidence of recrystallisation of quartz and its symplektitic intergrowth with feldspar.

The porphyroblastic granite-gneiss differs in the following respects from the criteria assembled by Willemse (1937, pp. 95, 100) for the Basement Granites of South Africa:-

(a) the composition is granitic, not granodioritic;
(b) modal potash feldspar > modal plagioclase;
(c) potash feldspar is characterised by microperthite, not microcline.

Since it is not within the scope of this thesis to embark on a detailed discussion of granitisation, the reader is best referred to the excellent discussion of the pertinent literature provided by Read (1944, pp. 47-87) wherein the above features reach sufficient significance to become criteria for granitisation. In this connection Brink (1950, p. 157) has suggested a temperature of 850°C for the formation of the microperthite, and Jansen (1956, pp. 4-5) regards the contemporaneous folding and granitisation of the Malmesbury Beds as indicative of synkinematic granitisation (cf. Williams, Turner and Gilbert, 1955, p. 229). The characteristics of this granite-gneiss agree in general with the criteria assembled by Marmo (1955, pp. 429-437) for synkinematic granites and granodiorites, except that this author emphasises the presence of microcline as the essential potash feldspar in pre-Cambrian granites. The relationship between plagioclase and potash feldspar supports Marmo's view that synkinematic granites have developed from earlier-formed granodiorites by potash metasomatism.

Brief references have already been made to evidence of mobilisation following the processes of granitisation. The relationships between granitisation and mobilisation have also been adequately discussed by Read (1944, pp. 87-89), but the present author has approached the problem from a somewhat different point of view. That a magmatic stage actually was reached in depth may be indicated by

Plate XVI.- Boulder conglomerate at the base of the Kuibis Series on Kruispad, showing irregular boulders of gneiss, and cavities from which they have been weathered, enclosed by arkose.

the presence of the two small veins of lamprophyre, and many small veins of pegmatite and of blue and milky quartz, both interfoliated and transgressive to the foliation of the granite-gneisses and metasediments in the area.

Mobilisation of the more highly granitised rocks might have led to the formation of a magmatic phase, during the existence of which anorthositic, pyroxenitic, lamprophyric, pegmatitic or aplitic and siliceous differentiates could have formed. These may subsequently have been emplaced in the random positions they occupy in the porphyroblastic granite-gneiss and its contact-zones. Thus the anorthosite, pyroxenite, lamprophyre and some of the acid differentiates are interfoliated in the porphyroblastic granite-gneiss, whereas the transgressive pegmatite and siliceous veins in the porphyroblastic granite-gneiss and metasediments represent later emplacements. No ore or economic minerals were observed in these veins, except small amounts of magnetite.

2. Sedimentary Formations Overlying the Archaean Complex

(a) The Nama System

The Archaean Complex is overlain by the sedimentary rocks of the Nama System, which is represented in the area by the Kuibis Series followed by the Lower Stage and part of the Middle Stage of the Schwarzkalk Series. The sediments overlie the older rock-types nonconformably, and have been formed from the products of their mechanical weathering. The consistent thickness of the Kuibis Series suggests that the pre-Nama surface must have been virtually peneplaned before the accumulation of sediments took place. Many local irregularities do, however, occur in it.

Irregularly shaped bodies of arkose occurring at some depth in the crystalline rocks, and especially those which are highly feldspathic and recrystallised, and apparently surrounded by granite, have created the impression in some quarters that the basal members of the Kuibis Series have been invaded by the granite. These features are, however, easily recognised as fillings in the ancient and exfoliated surface of the Complex. Furthermore, a sheer krantz on Kruispad (Plate XVI) exposes up to 40 feet of the succession from granite upwards to feldspathic sandstone where the sediments enclose rounded and angular granite boulders of all sizes. Each boulder displays a different direction of foliation, and some show exfoliation and other features of concentric weathering. Every conceivable form of fissure-filling exists between them. Consolidation of the arkose is often so advanced, however, that found elsewhere in the field, it might be mistaken for metaquartzite. It is perfectly clear, however, that the relationship of the Nama System to the Complex is purely sedimentary.

(i) The Kuibis Series. This series is represented by the following rock-types from the base upwards:- boulder conglomerate, conglomerate, limestone-pellet conglomerate, arkose, grit, feldspathic sandstone, sandstone, feldspathic quartzite and quartzite. Thin, intercalated shale bands occur in the finer-grained arenaceous rocks. The maximum thickness of the succession measured was 252 feet.

The conglomerates are lenticular and irregular. The common pebble conglomerates consist of sub-angular to well-rounded, well-sorted, white to pink, milky vein quartz, metaquartzite, limonite altered from magnetite, and flinty mylonite. These are usually found some distance upward from the contact. Nearer the base are sandstones honeycombed by cavities which formerly must have contained pebbles of clay or weathered granite. These have been flattened by pressure and completely leached, leaving only a little clayey matter and quartz in the casts. On Bushmans Graaf Water and Riet Kloof, a few feet of conglomerate immediately above the contact carry flattened limestone pellets in a sandy matrix. These pellets probably represent calcareous pods and nodules which formed on the pre-Nama granite surface.

In general, the succession becomes less feldspathic upwards. Selective recrystallisation of parts of the sandstone to quartzite has resulted in a peculiar banded structure parallel to the bedding. Dark pits in the quartzites and sandstones are attributed to the weathering out of iron oxides, probably derived from magnetite, garnet or clayey nodules, to judge from the limonite nodules which are still present in freshly broken rock. Thin seams of fossil "black sands" are occasionally encountered in association with grits.

Ripple-marked planes are not common but have been found locally, and current-bedding is present in the sandstones on Uilklip and Riet Kloof. This indicates subaqueous deposition of the latter members of the succession.

A shale band varying in thickness up to 4 feet

Plate XVII.- Erosion of Kuibis sandstone by stream undercutting along shale band on Riet Kloof.

Plate XVIII.- Limonite pseudomorphs after pyrite. Crystals weathered from Kuibis quartzite (large) and Schwarzkalk arkose (small). Scale in inches and centimetres.

generally occurs near the top of the succession (see Plate XVII). It is often sheared and slickensided. Other thin intercalated bands are also present, and on Bushmans Graaf Water one of these, instead of being sharply demarcated at the upper contact, passes gradually into sandstone.

Euhedral crystals of limonite pseudomorphous after pyrite are occasionally encountered in quartzite and sandstone near the base of the succession (see Plate XVIII). These are discussed more fully in Chapter VII.

(ii) The Schwarzkalk Series. This series overlies the Kuibis Series conformably. At the base, the lenticular limestones from which the series derives its name may or may not be present. A thin conglomerate containing pebbles of sandstone in a sandy matrix is sometimes visible in this position. On Riet Kloof a few feet of calcareous shale are exposed beneath the limestone.

The basal limestone, if present, is followed by a few more feet of limestone with intercalated calcareous shales, which in turn are overlain by fawn, blue or black shale, light-coloured flagstone, and more dark-coloured shale.

The Middle Stage, according to Jansen's subdivision of the series (1953; Coetzee and Jansen, 1953) then follows with arkose, grit, conglomerate and more arkose with intercalated shale bands, passing upwards into fawn, dark-blue and purple shales.

The succession of shale is very compact and fine-grained, but well jointed and fractured as a result of post-Nama tectonics.

The flagstone is present on Riet Kloof, Tafelberg Extension No. 2, Klein Banken and Brandewynskraal, where, owing to its resistance to erosion, it forms the crest of an anticlinal axis parallel to the other fold-axes. The flagstone is generally fawn in colour, and contains green, grey and white flinty or cherty bands.

The arkose represents a gradual change in lithology from shale to conglomerate. It is dark-green to dark-blue in colour but does not contain sufficient clayey matter to qualify for the term graywacke. It also contains many euhedral crystals of limonite pseudomorphous after pyrite, but very much smaller ones than those mentioned previously. They weather out of the arkose and can be picked up in handfuls. The laminated surface of the arkose is often wrinkled and bears linear marks which may have originated through the puckering of the unconsolidated sediments. Horizontal flowage with accompanying contortion and pinching is also illustrated by the cherty bands in the flagstone.

The grits and conglomerates represent the highest markers in the Schwarzkalk succession in the area. They occur over a total maximum thickness of ±100 feet; they are somewhat lenticular, but form fairly prominent features wherever they do occur due to their resistance to erosion. The lowest conglomerates appear at a variable height above the base of the series, the lowest being about 150 feet from the base on Leeudans.

The gravel in the grit is composed of quartz fragments only. The pebbles and small boulders in the conglomerates, however, are representative of all the older rocks: granite, red aplogranite, granophyric granite, vein quartz, granulite, metaquartzite, chalcedony, jasper and agate. The successive outcrops of conglomerate on Brandewynskraal and Klein Banken are due to repetition by folding. The lower conglomerate usually contains small pebbles in a clayey matrix, those of white vein quartz predominating. It is followed by grey mudstone or shale, then the upper conglomerate, which contains small boulders up to 6 inches in diameter. All the constituents of the conglomerates are well rounded except those from the metasediments, which are more angular.

(b) Tertiary (?) Silcrete

Patches of silcrete frequently occur in the south-west corner of the area, and also as isolated outliers on the slopes of prominent ranges of hills in the north central part of the area. The silcrete rests unconformably upon the older formations, which, except in one case of aplogranite, all belong to the Nama System. The altitude of the base of the occurrences decreases approximately 1,000 feet over 12 miles to the south-west. The maximum thickness observed was 15 feet.

The silcrete is formed essentially of angular fragments of vitreous quartz set in a fine siliceous matrix, with boulders and pebbles sometimes enclosed at the base. The rock is cream, fawn or light to dark grey when fresh, but weathers to a rusty, red colour.

Rogers (1912, p. 74) writes: "Surface quartzites of the kind described above.......belong to the same type of rock as the surface quartzite found in many parts of the west and south coast districts, and less often in the Langeberg region of Bechuanaland....". du Toit (1954, pp. 447-448, 460-461) has included these occurrences in his description of silcretes of the Coastal Region, but hesitates to assign any age other than pre-Pleistocene to them.

The majority of stone-age artifacts found in the vicinity has been made from silcrete.

(c) Recent Deposits

The Recent deposits in the area have been derived largely by the mechanical weathering of exposed rock-types. Quartz-feldspar sand generally overlies hardened clay, clayey grit or calcrete formed from alluvium on the one hand, and the weathering of granite in situ on the other. Small amounts of gypsum are present in dried pans and river-banks on the farms Kalk Gat Vlakte and Zoovoorby east of the area covered by Map 2 (see Chapter VII). On the flats in the extreme west of the area, well-rounded, water-worn pebbles of limonite-stained vein quartz, limonite pseudomorphs after pyrite, silcrete and shale are strewn over the surface.

Rubble consisting of pebbles and boulders of sandstone, quartzite, shale, silcrete and mylonitic flint commonly collects in the flat areas, forming slight terraces where not covered by sand.

Calcrete is found on the weathered surface of limestone, and also on granite and shale. Up to 3 feet below the surface of the general soil-cover, a gritty, reddish calcrete occurs in the greater part of the area covered by Recent deposits. The thickness of this calcrete is very variable, and it is considered to have formed by the cementing action of lime from decayed feldspars.

3. Intrusive Rocks

Dolerite dykes which are possibly of Karroo age, intrude the crystalline and sedimentary rocks on Riet Kloof and Puts. Further occurrences are known from Portion of Rietmond and Kamaboos, north of the area covered by Map 2, but these have not yet been investigated.

The southernmost occurrences strike roughly east-west and crop out intermittently over a distance of 5 miles, and are probably related to one another in spite of being

Plate XIX.- Post-Nama dolerite, showing alteration of pyroxene and well-disseminated opaque minerals. Plane polarised light. x 32. 19659, Riet Kloof.

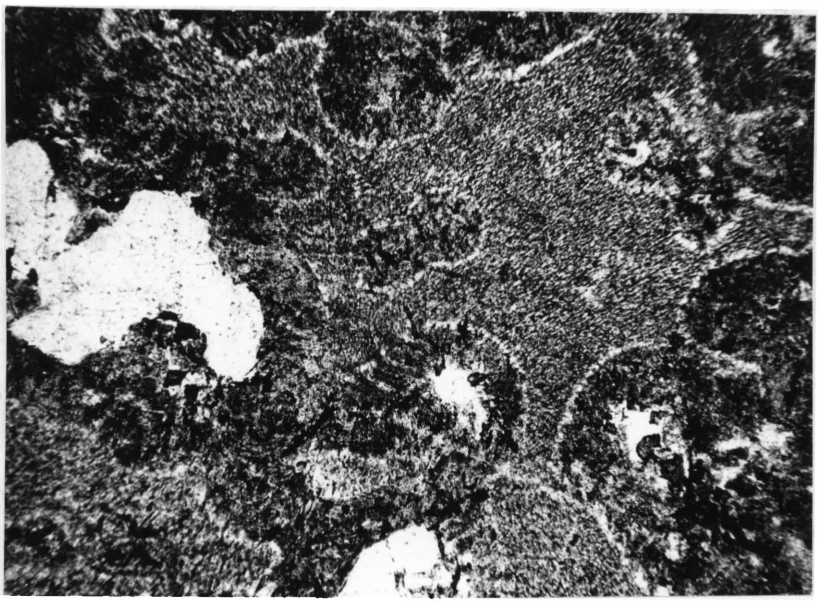

Plate XX.- Alteration and induration of potash feldspar in aplogranite country-rock by post-Nama dolerite. Note reaction rims around secondary alteration products of feldspar. Plane polarised light. x 32. 19662, Riet Kloof.

somewhat en echelon in distribution.

The rock is fine-grained and exhibits chilled phases at its contacts. Labradorite and augite in characteristic relationship, and disseminated pyrite, were identified from weathered samples (19659; Plate XIX).

The aplo- or porphyroblastic granite-gneiss wall-rock has been highly altered and indurated (19662; Plate XX). Much ferruginous matter has been released and appears along dark-coloured reaction rims. Plagioclase, crystallising in distinct laths, has been introduced. In the Kuibis sediments, the contact is also very ferruginous, and injection has taken place along the bedding-planes with some assimilation of the shale bands.

D. Structural Geology

1. Pre-Nama Structure

It is not certain whether the existing directional features in the metasediments are sedimentary in origin or were induced in depth prior to the regional granitisation of the area. In some cases, as the contact with the granite-gneisses is approached, it becomes irregular in strike and dip until such a degree of mobilisation is reached that no general strike or dip can be recognised. Seeing that the more reliable strike of the metasediments away from the contact corresponds on a regional scale to that of the correlatives west of this area, and closely parallels that of the granite-gneisses, it seems likely that such directional features were induced; the irregular features referred to most likely resulted from the local accommodation of original structures to correspond with the directional features which were induced in the more mobile levels of the granitised rocks. Dips are generally steep and would suggest that compression of the original strata had taken place, and so produced the contorted, overfolded or steeply dipping laminated effect that is especially characteristic of the metaquartzite and aplogneiss.

In the porphyroblastic granite-gneiss, proximity to the contact with the metasediments is accompanied by many local variations in the dip and strike of its foliation and lineation. At some distance from the contact, however, these directional features are more uniform, and show a gradual regional change in strike over the area mapped (see

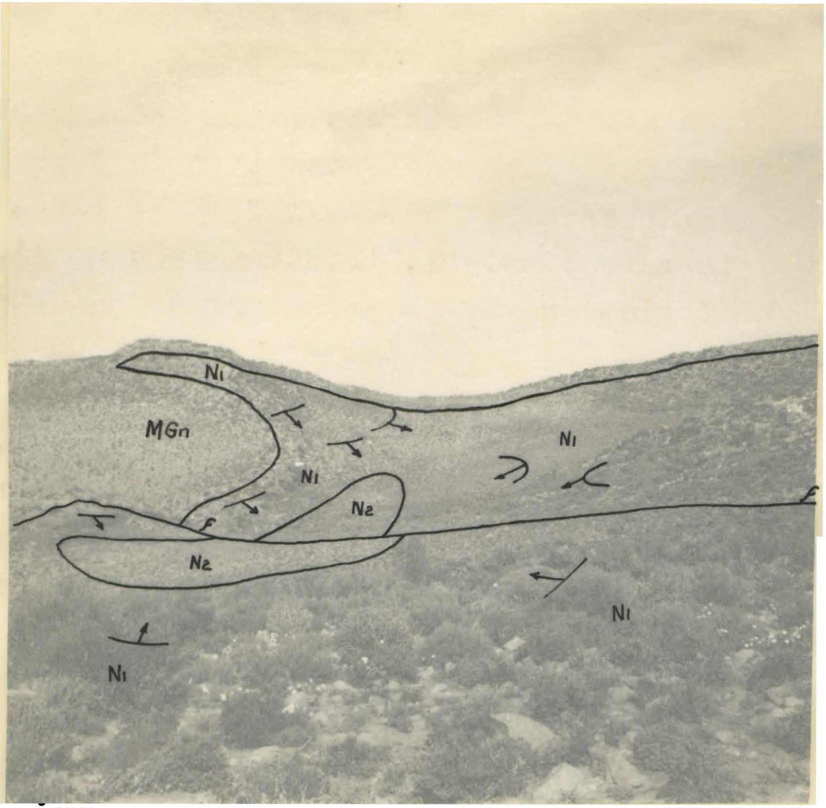

Plate XXI.- MGn, porphyroblastic granite-gneiss; N1, Kuibis Series; N2, Schwarzkalk Series. Arrows indicate dip of formations.

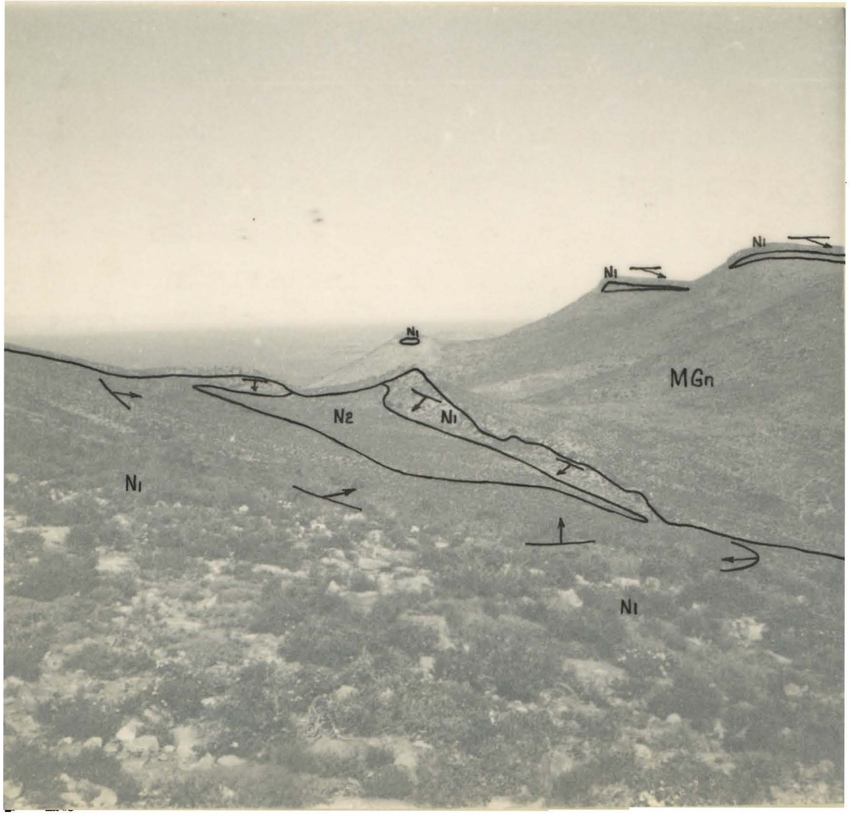

Plate XXII.- Syncline of Nama sediments on Riet Kloof passing into anticline on the right, of which only portions of the limbs remain.

Map 3). In the south and south-eastern corner of the area, the foliation strikes north-west; to the north of the area it changes gradually to west, and then further north and to the west of the area, it swings WSW. The lineation, where apparent, is more constant, trending in general WSW. The dip of the foliation varies in amount and direction; in general, however, it is to the south or south-west, and shallower in the south than in the north of the area.

Shear-zones and pre-Nama faults in the crystalline basement, with some exceptions, show a preference to trend roughly parallel to the strike of the foliation. Bearing in mind that the radioactive minerals on Steenkampskraal and to some extent on Roodewal, occur in zones of shearing, more than usual attention has been paid to similar features in the area.

In general, the shear-zones or faults are characterised by recrystallisation of quartz and some degree of hydrothermal alteration of the feldspars, with the production of epidote, kaolinite, limonite and chlorite. The large features are generally quartz-filled, and some bear faint stains of secondary copper minerals.

Post-alteration mineralisation of the shear-zones, if present, has taken place along the shear-planes at the expense of the easily replaceable alteration products. Such mineralisation has reached its best development in the known occurrences of monazite ore, but is also represented in other shear-zones in the area by barite on Uilklip, and disseminations of apatite and zircon, notably on Klein Banken, where concentrations of the latter mineral provide a higher radiometric normal than the surrounding metaquartzite.

2. Post-Nama Structure

Post-Nama tectonics are reflected in the long NNW.-trending ranges of hills in the area, which are the most striking features of the present-day topography. They are capped by Nama sediments which provide dip-slopes to the west and erosion scarps to the east (see Plates XXI, XXII). Flexure of the Nama crust, resulting in the formation of repeated folds with axes trending NNW., was followed by a lesser degree of flexure in a direction at right angles to the first, giving rise to canoe-folds, domes, pitching anticlines and synclines along the axes of the main folds, and

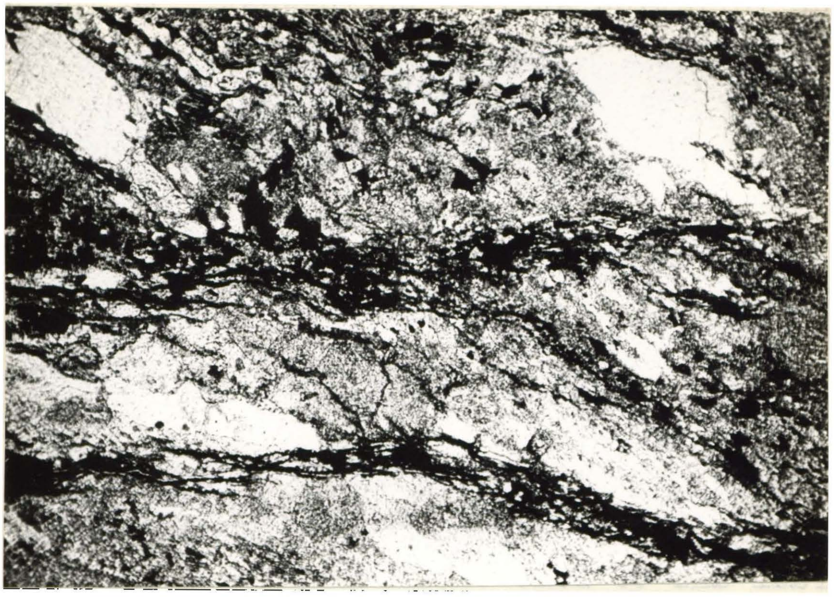

Plate XXIII.- Photomicrograph of flaser-gneiss subjacent to the Nama System, caused by differential movement between the crystalline basement and the overlying sediments during folding. Plane polarised light. x 32. 19684, Tafelberg Extension No. 1.

Plate XXIV.- Exposed surface of Kuibis quartzite folded and dipping steeply towards the observer, showing transverse tear-fractures resulting from flexure along limbs of syncline on Riet Kloof.

possibly to the dip-faults which occur in the Nama System. The folding has been accomplished by movement along joint-planes and fractures in the crystalline basement; flaser-gneiss and quartz-filled breccia containing parallel quartz veins has formed along the fold-axes for a few feet immediately subjacent to the Kuibis Series (19684; Plate XXIII). Severely mylonitised or brecciated granite characterised by the development of epidote, chlorite etc., is frequently found some distance below the sedimentary contact. Quartz veins filling fractures and joints are sometimes prominent in the crests of folds in the Kuibis Series; typical tear-fractures resulting from flexure are shown in Plate XXIV.

Distinct thinning of the Kuibis succession by attenuation has been observed on the steep limbs of nearly monoclinal folds wherever these limbs are still preserved. Fracturing and brecciation due to the sharp folding along the axes has favoured weathering and erosion, however, with the result that the structure as it exists suggests the action of regional step-faulting, as it was originally interpreted by Rogers (1912, pp. 14, 31). The preservation of some folds, with the criteria referred to indicate, however, that this is not the case. Only one strike-fault was found, on Tafelberg Remainder, and this occurred as a result of the folding, not prior to it. The attenuated strata are sometimes very difficult to locate, but they can be traced from the positions of the slight erosion terraces which they form.

From the number of minor folds which exist within the major features, it is concluded that the Nama folding has resulted in the formation of successive synclinoria and anticlinoria rather than synclines and anticlines. Very steep dips in the quartzites may result from these folds, especially where they pitch. The tectonics have given rise to contortion, overfolding, faulting, slickensiding and jointing of the strata, and abrupt changes in dip over short distances are sometimes necessary to accommodate these structures.

On Brandewynskraal, the crystalline and Kuibis rocks protrude through contorted Schwarzkalk shale. This feature suggests upthrusting of the basement along the axes of anticlinal folding which trend southwards from Riet Kloof. In another local "updoming" on Bushmans Graaf Water, the Kuibis quartzite protrudes through contorted Schwarzkalk shale and is actually overfolded to the south-west. It is inferred from these structures that wherever the shale appears to rest directly on the granite, as for instance on Leeudans, Tafelberg Remainder and Tafelberg Extension No. 2, it does so because the underlying Kuibis rocks have undergone severe attenuation. The feature is therefore interpreted as one of structure, and not of deposition on an uneven surface.

Dip-faulting is characterised by brecciation of the quartzite and infilling by quartz and limonite. Owing to the erosion of exposed strata, displacement cannot be measured, but it is of sufficient magnitude to result in the preservation in some cases of small areas of Schwarzkalk sediments on the downthrown sides. Slickensides are such a common feature that they are considered to result from differential movement along joints during folding, or from the collapse of the weathered crystalline basement beneath scarps of quartzite. A more reliable criterion for faulting is the extent to which brecciation has taken place.

Post-Nama, pre-Tertiary (?) quartz veining parallel to the strike of the Nama formations is prominent in the extreme south-west of the area. The vein contacts are unfortunately not exposed, but the presence of ferruginous, mylonitic material suggests that movement has taken place, and banding and comb structure in quartz indicate the filling of large fractures. The veins form slight ridges and terraces where they outcrop above the soil-cover. A small occurrence of quartz veining in the Schwarzkalk was found on Roode Kloof; milky quartz with comb structure is coarsely developed, filling joints and fractures transgressive to the bedding. This veining by milky quartz is no doubt related to the filling of fault-zones in the Nama System farther west.

III.- The Monazite Deposit on Steenkampskraal

A. History

As far as can be ascertained, the deposit had long been known to the local farmers, but had been dismissed as a small occurrence of iron ore on account of its dark-brownish colour. At some time prior to 1949, Mr. P.C. Schreuder of Vanrhynsdorp District, whose father had known of the deposit, handed a few samples of the ore to Mr. P.B. van Rhyn, who in turn referred them to Mr. M. Brink, his partner in a prospecting venture at that time. In 1949, Mr. S.A. le Riche, on Brink's behalf, sent samples for assay to Johannesburg (to a bank laboratory?) and to the Cape Copper Company at Nababeep, Namaqualand. On learning from the latter that they might be zircon-bearing ore, he sent a further sample to a friend in New York, who had it assayed by Dr. Bell of Lucius Pitkin, Incorporated. Dr. Bell cabled le Riche to the effect that the specimen was high-grade monazite ore. After ascertaining the nature and value of monazite, a proprietary company was formed by Brink and associates, and claims were pegged on the site of the deposit.

In August, 1950, the deposit was investigated, surveyed and sampled by the author, and the geological survey of the surrounding area was begun. In November a permit was issued to the company, Monasiet en Minerale Ondernemings (Edms.) Beperk, to mine and export 1,100 long tons of ore, on behalf of the Minister of Mines. The first consignment of 50 tons was despatched to Thorium Limited, London, on the 7th of December by Kava Import and Export Company, through Messrs. Dart and Howes, Cape Town.

It had already become obvious, however, to both the Department of Mines and the company, that the latter lacked the experience and equipment to exploit the deposit adequately. When the permit expired in November, 1951, the Anglo American Corporation of South Africa, Limited, was approached to prospect the deposit thoroughly on behalf of the company. On the strength of ore-reserves calculated from the results of diamond-drilling, the Corporation partially bought out the original company, and a new one, Monazite and Mineral Ventures (Pty.) Limited, was formed. This company was then granted permission to mine the ore, concentrate the monazite and export the concentrate on behalf of the Minister of Mines, and has since been operating successfully at Steenkampskraal. The rôle played by the Corporation in developing this proposition from a small, opencast venture to a smoothly operating mine and ore-dressing plant at an isolated point in the wastes of the Knersvlakte is described in detail by MacConochie (1947, pp. 95-100).

Plate XXV.- The western half of the ore-body on Steenkampskraal as it outcropped originally, forming the dark-coloured ridge protruding from the lighter-coloured granite-gneiss surface.

Plate XXVI.- The original outcrop of the ore-body (dark, stratified appearance) enclosing xenoliths of altered granite-gneiss (light colour, around and to the right of the prospecting pick). Steenkampskraal.

B. Location, Size and Nature of the Deposit

The ore-body is an elongated deposit near the top of a prominent koppie of porphyroblastic granite-gneiss* . It extends over the ridge of the koppie from east to west, slightly to the north of the summit, and it is best developed on the western slopes (Plate XXV). It dips fairly steeply southwards at varying angles depending on the attitude of the shear-zone which it occupies, but quite independently of the foliation in the country-rock. According to Bateman's classification of ore-deposits, the Steenkampskraal ore-body constitutes a lode fissure replacement deposit (1947, pp. 103-104, 364).

The koppie is approximately 150 feet high, and is considerably steeper on the eastern than on the western slopes. An east-west trending zone of strong jointing has produced a slight saddle in the crest-line of the koppie towards its northern end, and the ore-body trends across the southern slopes of this saddle. The abrupt termination of the koppie to the north and south is due to two more zones of east-west jointing and shearing, which have provided zones of relatively easy weathering.

The ore-body has been emplaced epigenetically in the form of nearly parallel lodes and stringers which replace alteration products along a conspicuous shear-zone in the granite-gneiss (Plate XXVI). The shear-plane, at the surface, dips more steeply than the foliation of the granite-gneiss (see Map 4). The truncation of the foliation by the shear-plane is quite distinct, and a clear indication that the shearing was independent of the formation of the granite-gneiss.

The deposit strikes due east-west for all practical purposes, and it has a distinct, though variable, dip to the south, averaging 57° in the middle of the western half. The outcrop tends to conform to the general contours of the koppie, but each extremity shows a definite change in strike to the south-east and south-west respectively, which suggests a saucer-shaped attitude for the deposit.

The outcrop of the ore-body is 933 feet long. The width varies from a few inches at the eastern extremity to a maximum of 13 feet in the middle, decreasing again

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* For the sake of brevity, the porphyroblastic granite-gneiss will be referred to as granite-gneiss from now on.

Plate XXVII.- The widest outcrop of the ore-body on Steenkampskraal, forming the dark-coloured "blow" to the right of the Native.

Plate XXVIII.- View of Brink's prospecting pit, looking eastwards. The southerly dip of the lode is quite distinct. The steep joints nearly parallel to the strike are post-mineralisation in age. The light-coloured material is altered granite-gneiss wall-rock. Steenkampskraal.

towards the western end; a width of 40 inches is maintained as an average over the western half. The greatest width of outcrop is due to a local change in strike accompanied by a shallowing of the dip (Plate XXVII).

At the time of the first investigation, the persistence in depth of the deposit could only be surmised; a prospecting pit made by Monasiet en Minerale Ondernemings showed the ore-body to persist to a depth of 5 feet without decreasing in thickness (Plate XXVIII). Shallow prospecting trenches, not more than 2 feet in depth, were made across the deposit at intervals along the suspected outcrop for the purpose of tracing its continuity, and also at the western extremity, but these were too shallow to reveal its behaviour. Diamond-drilling by the Anglo American Corporation subsequently proved the continuation of the ore-body in depth to over 400 feet measured vertically from the surface.

Variations in the width of the bore-hole intersections were interpreted as resulting from the pinching and swelling of the ore-body, laterally and vertically, in the same way as it does on surface. This has since been borne out by underground development. The depth of the intersections showed the dip to decrease markedly after a certain depth, then to increase again to its former angle, and to be generally steeper on the western than on the eastern extremity. This has also been borne out by underground development (see Fig. 7, p. 60).

The original ore-body stood out from the country-rock in marked relief (Plate XXV), revealing more resistance to weathering than the surrounding jointed and sheared granite. The dark-brown colour of limonite-stained monazite, with occasional green patches of secondary copper minerals, also provided a conspicuous contrast in colour from the light-coloured granite-gneiss.

C. Prospecting Methods

Prospecting done under the supervision of the author during 1950 was restricted to the making of shallow trenches across the strike of the deposit as described, and to traversing it at regular intervals with a Geiger-Müller counter. The purpose of these radiometric traverses was to determine whether the country-rock contained any radioactive material as well, and whether the ore-body could be traced in depth through any anomaly recorded on the hanging-wall side of the deposit. The results proved negative in both cases, but were nevertheless valuable in that they indicated the extent to which float from the deposit was distributed (see Fig. 4 and Map 5). The instrument used was a Victoreen 263A β- and γ-Field Counter. γ- and β+γ-radiation was recorded at intervals of 5 paces along traverses 25 to 35 yards apart, as nearly perpendicular to the deposit as possible. The length of each traverse was made from background radiation on one side of the deposit to background radiation on the other side (see Map 5).

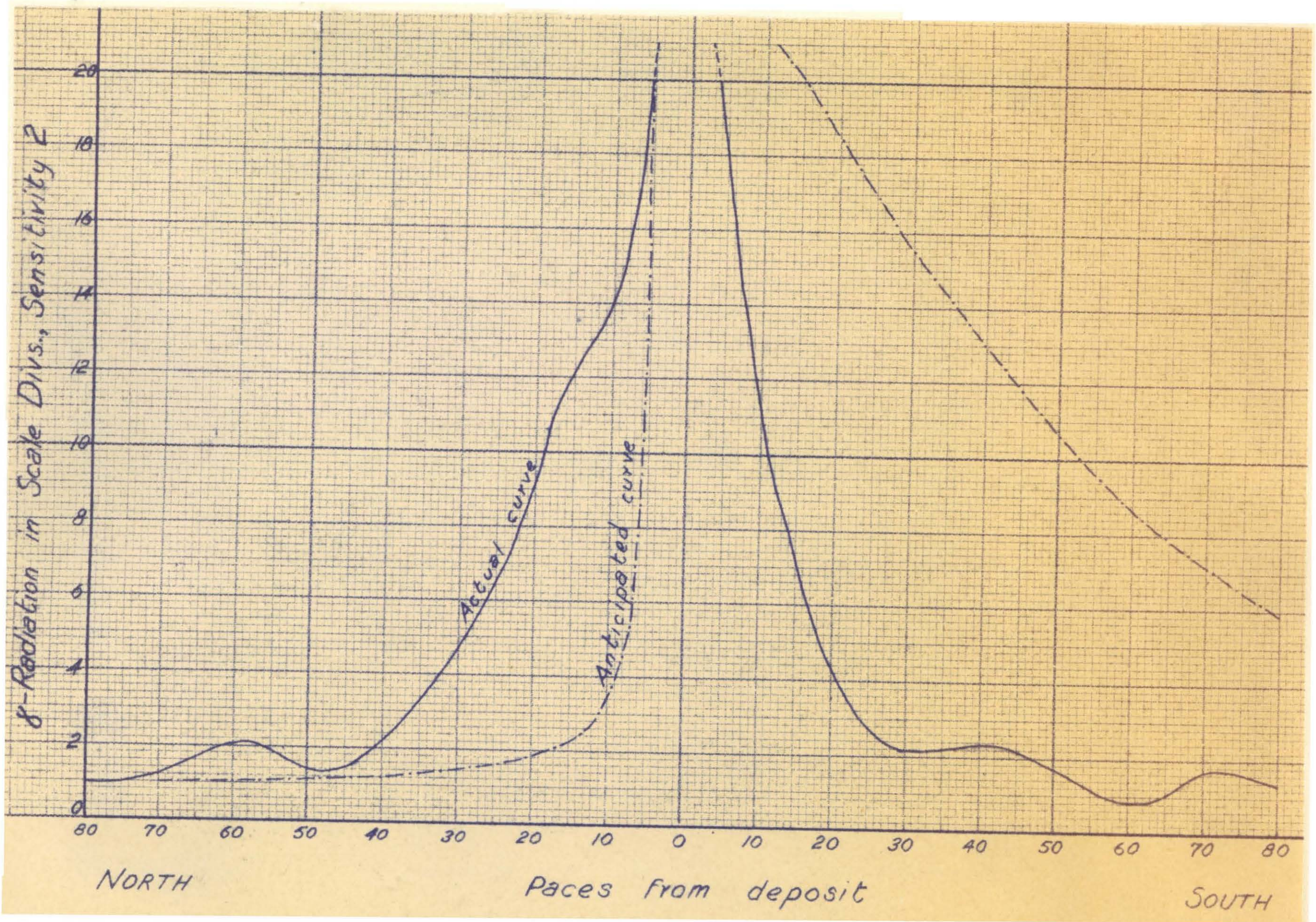

Fig. 4.- Average radiation from seven consecutive traverses over the western half of the Steenkampskraal monazite deposit.

As the results of sampling done by the author were promising, it was suggested that a series of diamond-drill holes be sunk on the hanging-wall side of the deposit to intersect it at depth. This drilling programme subsequently formed the basis for the prospecting carried out by the Anglo American Corporation. The results were used to calculate ore-reserves of at least 250,000 tons, and at the same time information was obtained about the tenor of the ore at depth, and the behaviour of the ore-body.

Table No. 3.- Results of Diamond-drilling on Steenkampskraal

Bore-hole No.	Incl. in degrees	Collar elevation from datum	Depth of Intersection		Thickness of Intersection			Depth Stopped		Details
			Inclined from surface	Vertical from datum	Inclined	Vertical	True	Inclined from surface	Vertical from datum	
1	60	-608'	208' to 211'	-788' 1.3" to -790' 8.4"	3' 0.0"	2' 7.1"	1' 11.0"	312'	-878'	
2	60	-600'	282' to 284'	-844' 2.4" to -846' 0.0"	2' 0.0"	1' 9.6"	1' 11.9"	328'	-884'	
3	75	-604'						606'	-1093'	No lode.
4	60	-608'	256' 2" to 259'	-829' 9.6" to -832' 3.6"	2' 10.0"	2' 6.0"	2' 6.0"	278'	-849'	
5	60	-625'	317' to 321'	-899' 7.2" to -903' 0.0"	4' 0.0"	3' 4.8"	1' 11.9"	340'	-919'	10.6" monazite ore / 6.9" waste / 1'2.6" monazite ore.
6	90	-599'						422'	-1021'	No lode.
7	90	-609'	255' to 256' 8.0"	-864' 0.0" to -865' 8.0"		1' 8.0"	1' 2.9"			
8	60	-646'	350'	-949' 1.3"				450'	-1036'	Mineralised zone just recognisable.
9	60	-655'	258' 9" to 270' 4.5"	-879' 1.3" to -889' 2.4"	11' 7.5"	10' 1.1"	10' 4.2"	299'	-914'	Internal granitic waste 3'7.5" / monazite ore 6'8.7"
10	60	-674'	290' 5" to 292' 4.5"	-925' 6.0" to -927' 1.3"	1' 11.5"	1' 7.3"	1' 11.3"	344'	-972'	
11	60	-711'	385' to 385' 2.5"	-1044' 4.9" to-1044' 7.2"		0' 2.5"	0' 2.5"	424'	-1078'	
12	60	-710'	228' ?	-908' 2.6" ?			1' 6.5"	322'	-989'	4.5" monazite ore and two 7" bands of granitic waste.
13	45	-609'	238' to 238' 6.5"	-777' 2.6" to -777' 8.4"	0' 6.5"	0' 5.8"	0' 6.5"	256'	-790'	0.5" ferruginous ore / 5.5" good ore / 0.5" ferrug. ore.

Table No. 4.- Calculation of Ore-reserves to a Depth of 10 feet

Footage along deposit	Length in feet	Average true width	%eThO$_2$ (sampling)	Average %eThO$_2$	S.G.	Average S.G.	Short tons, assuming 10' penetration
523 - 572	49	41"	5.559		3.86		
			6.415	5.987	4.60	4.23	220.6
296 - 439	143	65"	6.755				
			6.586		4.01		
			4.571				
			6.290	6.051	4.25	4.13	997.0
Total short tons running ± 6.0%eThO$_2$.........							1217.6
173 - 222	49	39"	4.804	<4.804	4.20	4.20	208.6
90 - 151	61	39"	3.419	>3.419	3.75	3.75	231.9
Total short tons running ± 4.0%eThO$_2$.........							440.5

The results of the first thirteen bore-holes appear in Table No. 3, where the depths of intersections are given both from the surface of the ground and from an arbitrary datum 2,000 feet above sea-level. The sites of the bore-holes are shown on Map 5.

D. Sampling

In order to effect comprehensive assays of the thorium-content in the deposit, it was chip-sampled across its width at intervals of approximately 50 feet, as shown in the assay sheet (Map 6). The samples, taken over widths of 5 to 14 inches, were finely ground and radiometrically assayed for equivalent ThO_2 relative to a standard sample containing 4.6% ThO_2 and 0.04% U_3O_8. The accuracy of the standard later became suspect, however, and on being chemically assayed, it proved to have a radioactive content higher than that quoted. A suite of the samples was then radiometrically assayed using a standard obtained from Thorium Limited, London, containing 5.6% ThO_2 and 0.11% U_3O_8, and a factor was calculated from the results, with which the values previously obtained from the other samples could be corrected. The resulting percentages were converted into inch per cent values; these were corrected for dip, and were then plotted on the assay sheet.

Four sections of the deposit yielding a true channel-width of 30 inches and over have been indicated on the assay sheet. Specific Gravity determinations on samples from each of these four sections enabled approximate tonnages at an average per cent value to be worked out, assuming a depth of penetration of 10 feet without change in channel-width. The results (see Table No. 4), calculated to a depth of 10 feet, indicated an ore-reserve of:-

1,200 short tons running ± 6% $eThO_2$
400 " " " ± 4% $eThO_2$.

The results of underground sampling by the Anglo American Corporation on the 100-foot level of the mine have been indicated graphically on the assay sheet as well.

E. Country-rocks

1. Porphyroblastic Granite-gneiss

(a) General Description

The granite-gneiss which forms the country-rock to the ore-body is fairly typical of that occurring throughout the area.

Porphyroblasts of microperthite up to 10 cms. in length are set in a medium-grained ground-mass of orthoclase, quartz, plagioclase and accessories. The texture varies from that of an equigranular to that of a porphyroblastic granite-gneiss, and the composition varies in respect of the accessory minerals garnet, biotite, chlorite, titaniferous magnetite and ilmenite. The ore-minerals and garnet are generally well disseminated. The granite-gneiss is somewhat banded on its contact with the ore-body due to varying degrees of impregnation by limonite and green copper minerals. Differences in texture and mineralogy are gradational; the features which display these differences are relatively small, and they are so irregular and unrelated that it proved impossible to map them separately.

The foliation is provided by the grains of biotite and quartz in flow-layers separated by sub-orientated porphyroblasts, with the result that the rock often resembles an augen-gneiss in appearance. Mica-free quartz-feldspar schlieren also separate the flow-layers.

The lineation, where apparent, is brought out by elongated aggregates of recrystallised quartz and stringers of garnet, and by the sub-orientation of the porphyroblasts.

The structure of the granite-gneiss forming the koppie, relative to the regional directional features, is indicated in Map 7. The "whorl" which becomes evident on tentatively joining the strike-lines of the foliation might suggest some structural weakness with which the shearing or mineralisation, or both, could be associated, since it is not a common feature in the area.

Pegmatites in the granite-gneiss are characterised by pink feldspar. There is no apparent control with regard to their emplacement, for they display no definite trend, have gradational contacts, and are jointed and sheared together with the rest of the granite-gneiss. The aplogranite has similar features, but is generally interfoliated and shows the striking development of almandine in clots and aggregates up to 2 inches in size, in contrast to the finely divided garnet in the granite-gneiss (see Plate VII). Pegmatitic material occurs in the mineralised shear-zone at the first pinching out of the ore-body east of its thickest exposure, and at its western extremity. In places this material exhibits slickensides and alteration along with the granite-gneiss.

Near the eastern end of the deposit and stratigraphically above it, dark-coloured bands of biotite granulite transgress the foliation of the granite-gneiss (Plate XIII). They vary in thickness up to a maximum of 3 inches, but are persistent and may be traced up to 300 feet or more along the strike. They trend roughly east-west and dip to the south. Only one was suitably exposed for plotting on the field-sheet (see Map 4); it dies out to the east, but its western end was covered by scree and could not be traced farther.

The main constituents of the biotite granulite are microperthite, andesine and biotite, containing well-developed sagenite; accessory minerals are apatite, magnetite, pyrite and zircon (16882, 17941). The biotite is usually altered and replaced by the first three accessories. The origin and rôle of these transgressive granulites has already been discussed.

During underground development on the 200-foot level of the mine, the face of the east drive at one stage gave a dip-section of these granulite bands transgressing the granite-gneiss foliation, and the ore-body transgressive to both the granite-gneiss and the granulites, thereby bearing out the age relationship once more. The bands of granulite have undergone alteration in the vicinity of the shear-zone in the same way as the granite-gneiss has. At the surface, these bands weather more easily than the granite, and give rise to zones of weakness in the more massive rock (see Plate XIII).

(b) Joints and Shears

There are three main zones of joints and shears in the granite-gneiss (see Map 4). The middle zone forms the saddle already referred to, and is bounded on the north and south by two conspicuous bands of sheared and altered granite, the monazite ore-body occurring in the better developed southern one. The other two wider zones constitute the southern and northern slopes of the koppie. Each is separated from the others by comparatively massive rock which forms the highest points of the koppie, but in the zones themselves, shear-planes and well-jointed areas may be separated by more massive granite-gneiss as well. Each zone has dominant jointing in an east-west direction, and two or more transverse directions of lesser magn~~et~~itude.

The joints dip at varying angles, in general towards the more massive granite in the middle of the koppie. In the southern zone they dip steeply northwards, and in the northern zone they dip southwards, becoming vertical in the middle zone. Conspicuous quartz veins occur in the southern zone, presumably along similarly trending joint-planes.

The joints in the massive granite-gneiss were mapped for a radius of about 100 feet about the beacon GRAN (see Map 4), and some idea may therefore be gained of the frequency of their occurrence in the well-jointed zones. The azimuth diagram of these joints (Fig. 5) indicates their even distribution in the more massive granite, relative to the main direction of shearing. Most of the joints striking north-south and ENE.- WSW. appear to be Q- and S-joints, because they are perpendicular and parallel to the lineation respectively. East-west jointing which is unrelated to the primary flow-features of the granite-gneiss, however, becomes dominant as the shear-zones, which also trend in that direction, are approached. These east-west-trending

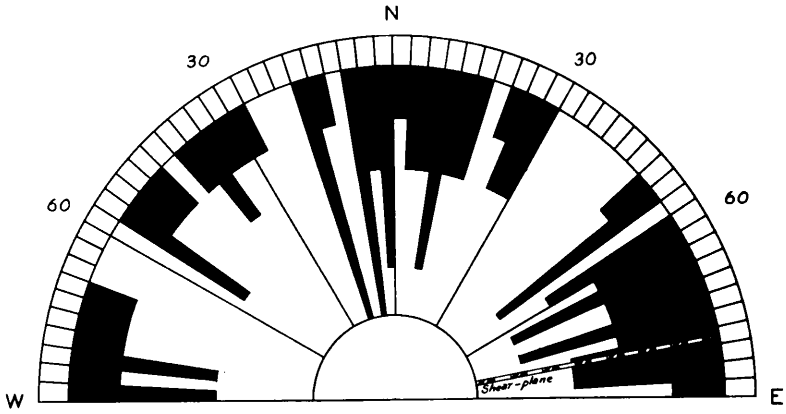

Fig. 5.- Azimuth diagram of joints occurring in massive granite-gneiss, Steenkampskraal.

joints, therefore, appear to be related to the shearing of pre-mineralisation age. On the other hand, joints are also developed which intersect the ore-body, but are not filled by alteration or epigenetic products; these must therefore be of post-mineralisation age. In particular, steep jointing has taken place at a slight angle to the strike of the deposit, corresponding in trend with the east-west joints in the immediate granite-gneiss. Post-mineralisation transverse joints also occur in the ore-body but they are not well developed.

Shearing has in each case produced a characteristically fine-grained, greenish mylonite. There is often a dark-coloured, ferruginous, schistose core to this material; vein quartz, flinty material and aggregates of brecciated quartz and feldspar make up the rest. Gradational alteration increases from the granite towards the core through brecciated feldspar, recrystallised quartz and chloritic material. The zones of shearing vary in size from a few inches to a few feet in width, and from a few yards to over 900 feet in length; their extremities pass into joints.

Apart from the best-developed shear-zone in which the monazite mineralisation has taken place, none of the mylonites in the other shear-zones is radioactive.

The examination of thin sections cut from different mylonites provides interesting results (18127-18132). It is difficult to generalise about their properties, since the degree of deformation, recrystallisation and replacement by younger minerals varies from shear to shear, but the following is a summary of their characteristics.

Essentially, the sheared material consists of a fine-grained ground-mass of alteration products derived from feldspar and mica <u>viz</u>. sericite, chlorite and quartz; the original feldspars are sometimes preserved as augen, rolled out between grains of quartz, but they are seldom recognisable. Sericite forms spherulites and ophitic intergrowths with quartz, indicating complete recrystallisation of the sheared and altered granite-gneiss. Quartz is the youngest mineral present, and is well-developed, replacing the ground-mass. The crystals are usually zoned or show internal recrystallisation shadows between crossed nicols. Narrow veins transgressing the quartz are lined by layers of chalcedony, sometimes limonitic and often containing a limonitic core. Magnetite has been altered to limonite and leucoxene. Euhedral apatite, and rounded to euhedral zircon, strongly zoned, have been introduced and are disseminated throughout

Plate XXIX.- Recrystallised but unaltered porphyroblastic granite-gneiss near the shear-plane, showing linear recrystallisation of quartz in feldspar. Scale in inches.

the ground-mass. Their association with the more coarsely grained mylonite and truncation of flaser-structures may be indicative of post-deformation mineralisation.

(c) Altered Wall-rock

(i) General. The altered granite which the ore-body replaces is confined to the zone in which shearing took place. It seems likely that a number of parallel planes of movement were formed, between which horses of granite-gneiss remained. These now appear as xenoliths completely surrounded by ore.

The degree of alteration in the granite-gneiss increases towards the ore-body. The feldspar first becomes red and is then replaced by sericite. The plagioclase gives way to epidote or zoisite, and they in turn to chlorite. The biotite is altered to chlorite as well, and chlorite and the ore-minerals to limonite. Where the altered wall-rock remains unreplaced by ore, it is represented by a structureless aggregate of quartz and clayey matter, stained various hues by secondary copper or iron minerals, or both. This material has been encountered in masses up to 3 feet thick on either side of the ore-body in the 200-foot level east drive. Quartz remains as nodules in the clayey mass which represents the original feldspar, and which contains spots of ferruginous matter representing the original biotite.

The degree of alteration is, however, not constant either laterally or vertically. As a rule the immediate wall-rock is very soft, but there are places underground and on surface where the alteration is restricted and the recrystallisation of the granite-gneiss is quite distinct. The recrystallisation is best observed in the quartz but is also apparent in the feldspar, and as in the case of the alteration, increases in intensity from the granite-gneiss towards the ore-body. The most common product is a granophyric granite composed of deep-red feldspar intergrown with sub-graphic, linear, vitreous quartz (Plate XXIX). This type may also give way to very coarse development of the feldspar, in which case the rock resembles pegmatite. Brecciation of the wall-rock followed by recrystallisation has given rise locally to the formation of aplitic material characterised by very red feldspar. On the 300-foot level, recrystallisation has in places proceeded in conjunction with the shearing movement, and has produced a hartschiefer. Transition phases occur between the latter and the foliated granite-gneiss. The tendency to banding, through recrystallisation of both quartz and feldspar, becomes stronger

Plate XXX.- Recrystallised porphyroblastic granite-gneiss wall-rock (hartschiefer) at shear-plane, showing distinct bands of quartz and feldspar giving way to bands of quartz and talcose material. Scale in inches.

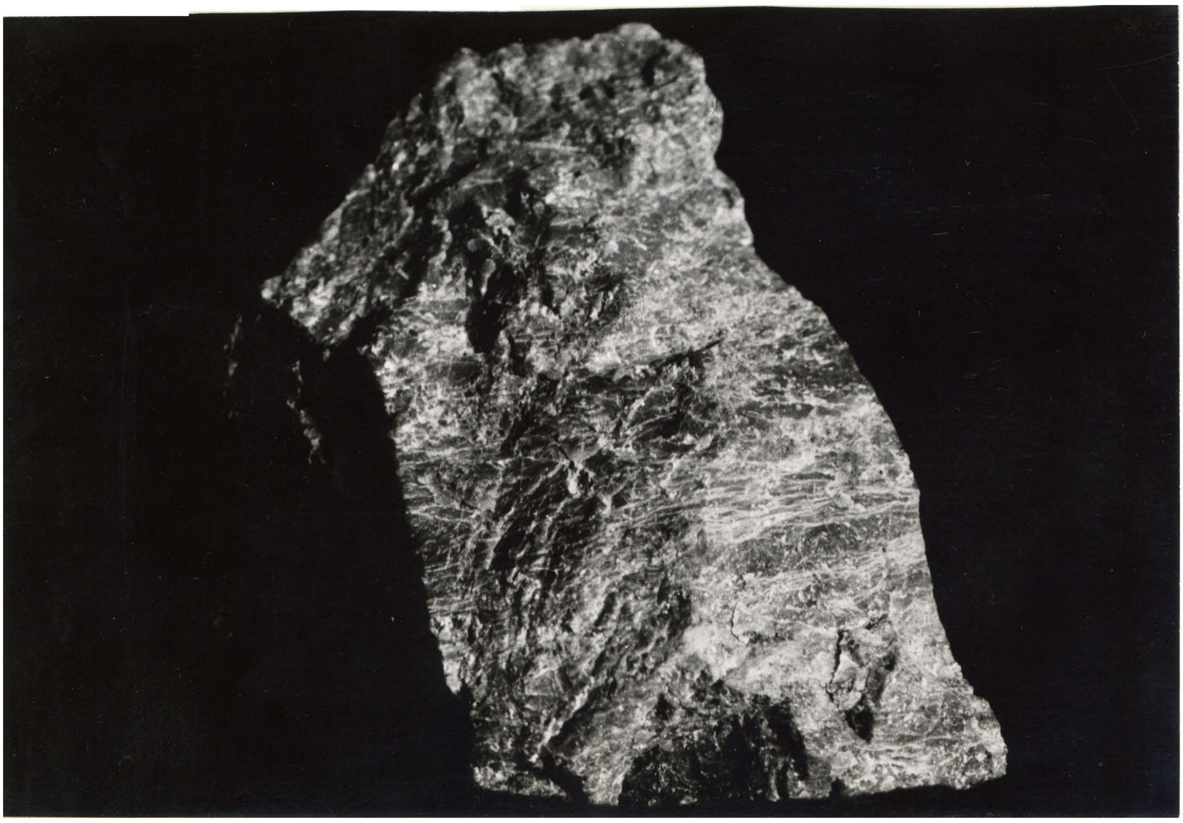

Plate XXXI.- Veins of malachite in massive chloritic wall-rock. x 1.5. Steenkampskraal.

towards the shear-plane. The feature is the more striking because the apparent "leaching" of either of the two minerals in different phases presents a massive, relatively quartz-free feldspar rock on the one hand, and a banded, relatively feldspar-free quartzose rock on the other. In hand-specimen, the hartschiefer is well banded as a result of the alternating zones of quartz and feldspar, the latter becoming altered and giving way to chloritic, talcose material at the plane of shearing itself (Plate XXX).

The alteration which has been described is applicable to both foot-wall and hanging-wall.granite-gneiss. At the surface the wall-rock is very distinctly fractured and weathered, and it is generally represented by ferruginous, chloritic quartz-clayey matter, containing locally-developed bands of dark-coloured secondary minerals. Slickensides and striated veneers of secondary minerals are common. Quartz veins are generally shattered and are stained by limonitic material. Stringers of malachite vein massive chlorite and talcose material (Plate XXXI), and have also developed in cracks in the adjacent unaltered granite-gneiss; other cracks are filled by azurite. Lining the veins of malachite are thin layers of a soft, apple-green, mamilliform, talc-like mineral, which is probably another secondary copper compound. Apart from the effect of surface weathering, there is very little difference between the surface and the underground wall-rock.

A mottled, green rock occurs in the stopes between the surface and the 100-foot level, consisting of partially altered feldspar replaced by malachite. The mottling is enhanced by the irregular dissemination of monazite ore in the rock (see Plate XXXII).

Secondary haematite resulting from the alteration of titaniferous magnetite occurs in fine to coarsely crystalline aggregates, especially in the foot-wall, and shows ready alteration in hand-specimen to whitish leucoxene. The foot-wall underground is especially characterised by the development of massive, red feldspar in granophyric or pegmatite-like rock. It contains disseminated and often coarsely-developed sulphides, and often bands of haematite, chloritic material and stringers of ore as well. The most striking development of hartschiefer was also observed in the foot-wall on the 300-foot level.

Plate XXXII.- Monazite (dark, granular) and malachite (grey) impregnating altered feldspar (light-coloured). "Mottled ore". Steenkampskraal. Scale in inches.

(ii) Petrography. The following thin sections were cut from samples of the wall-rock:-

Hanging-wall - 17942,17944-17946, 18118-18126, 18136.

Foot-wall - 17943, 17947-17949, 18111-18117, 18141, 18148, 18152.

Of the feldspars, orthoclase is generally more altered than plagioclase. Cleavage-traces can still be recognised, but they are distorted and have been filled by alteration material. The orthoclase is translucent: pale brick-red in colour by reflected light, and brownish-red with a pitted surface by transmitted light. The colouration becomes less away from the ore-body, and is attributed to the introduction of secondary iron oxides resulting from the alteration of the ore-minerals already present in the granite-gneiss.

The main alteration product is sericite, passing into small but distinct plates and laths of muscovite, sometimes in fibrous and radiating aggregates. Iron and copper sulphides and iron oxides are disseminated throughout the altered parts of the feldspar, replacing it irregularly.

Plagioclase may be recognised by its characteristic polysynthetic twinning even when highly altered. Even where the subhedral plagioclase crystals are entirely represented by alteration products, it is still often possible to recognise their original outlines. The alteration products which can be identified are sericite, epidote and zoisite (Plates XXXIII, XXXIV). They are generally very fine-grained in the body of the plagioclase; discrete grains of epidote and zoisite have developed externally to the plagioclase in the ground-mass as well. The most striking occurrence of epidote is in the highly altered rock containing disseminated ore-minerals at the eastern extremity of the ore-body. The presence of epidote seems to be characteristic of the wall-rock alteration at the present ground surface and at shallow depth. It occurs in irregular zones and aggregates (16679, 16680), and is concentrated with other alteration products in the vicinity of the introduced ore-minerals.

Zoisite occurs together with the epidote, and in the same manner, in the thin sections cut from drill cores at the intersections of the ore-body in depth (18503-18511). It is distinguished from epidote by its positive interference figure. Its concentration around xenoliths of wall-rock might be the result of interaction between the latter and the Ca-rich phosphate ore (18510). It is slightly pleochroic from pale green to pale olive-green, with absorbtion $\beta > \alpha$. The alteration of plagioclase to zoisite along cracks and cleavages is striking, and there is also distinct alteration of zoisite to chlorite.

Biotite shows the greatest resistance to alteration, being in some cases the only remaining representative of the wall-rock. The flakes may be very deformed, yet show no alteration. Usually, however, the biotite occurs in corroded or truncated fragments surrounded by zones of epidote and chlorite. It is altered to different degrees to chlorite, and its replacement by the metallic oxides and sulphides increases in intensity towards the ore-body. Some basal sections show sagenite inclusions partly altered to leucoxene by reflected light. Streaks and flows of much-altered biotite in quartz are now largely represented by secondary iron oxides which preserve the original lath-like outline of the mica. Chlorite occurs in fibrous aggregates, spherulites, flakes and laths, and sometimes in small veins, throughout the altered rock. Intergrown sericite and chlorite are occasionally observed near quartz. Iron and copper sulphides and iron oxides frequently replace biotite and chlorite. The impregnation of the micas by these ores along their cleavage-planes is very conspicuous.

Quartz is the youngest primary mineral. It often replaces the older rock extensively as irregularly shaped bodies having rounded contacts. "Flow structure" parallel to these contacts is not uncommon, and there is evidence that shearing took place obliquely to the direction of lineation of the quartz grains. The bodies of quartz vary in size from granules to veins 3 feet long and a few inches wide.

Fine veins of siderite a few millimetres wide transgress the altered wall-rock in some localities (18151). They probably represent a very late stage of mineralisation, since they are younger than all the foregoing minerals, yet they have undergone sufficient alteration to become stained by ferruginous matter in places. The individual crystals are very small, and give rise to comb structure in the veins, growing perpendicularly to the walls from all sides. A rough determination of the refractive indices by the immersion method gave $\varepsilon \div 1.630$, $\omega > 1.790$. A wet test for iron by precipitating the hydroxide was positive.

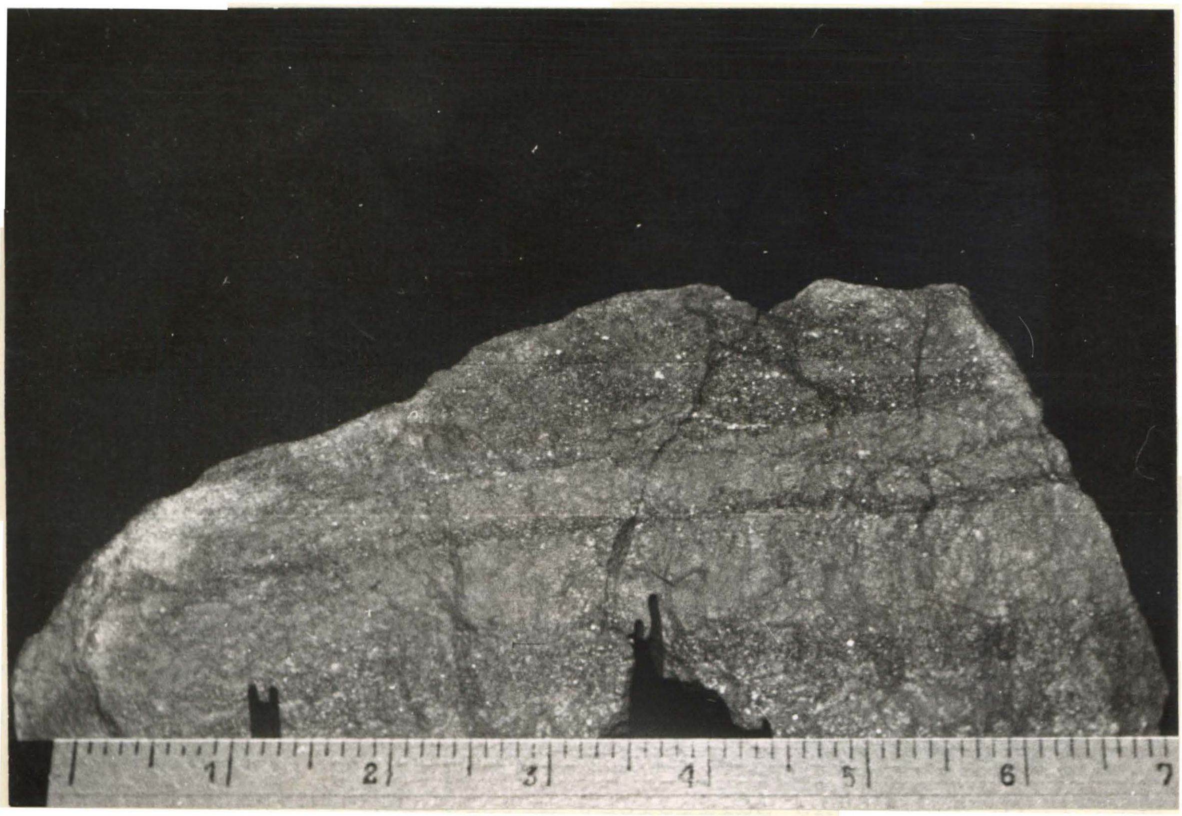

Plate XXXV.- Parallel veins and stringers of monazite ore in feldspathic wall-rock. Steenkampskraal. Scale in inches.

2. Nama Rocks

The base of the Kuibis Series is exposed in an elongated outcrop striking north-south and dipping to the west, 325 feet from the western end of the ore-body. The Kuibis rocks are definitely not in contact with the ore-body at present, and taking into account the amount of dip of the sediments, the difference in altitude between them and the ore-body, and the restricted distribution of float from the latter, it seems doubtful that they ever could have been in contact with the ore-body. However, the erosion that removed so much of the Nama rock could have removed much of the ore-body as well, thereby creating the impression that the two could not have been in contact. Radiometric traversing across the drainage pattern from the ore-body has, however, failed to reveal such quantities of detrital radioactive material anywhere within the surrounding area.

Lithologically, the Kuibis Series comprises coarse-grained arkose at the base forming a clearly sedimentary contact on weathered and well-jointed granite-gneiss; this is followed by feldspathic sandstone and feldspathic quartzite. A horizon of ferruginous sandstone occurs some distance above the base of the series. It is fairly persistent, varying in thickness up to a few feet, and varying between coarse and fine arenaceous phases. None of these sediments contain any radioactive material.

F. Geology and Mineralogy of the Deposit

1. Structure and General Geology

The relationship of the ore-body to the hydrothermally altered material in the shear-zone has already been mentioned briefly. The ore-minerals occur in a lode which swells and pinches within the confines of the shear-zone, and in places pinches out altogether. This is partly due to a mere lack of ore-minerals at these points, or due to post-mineralisation faulting along the direction of strike.

In places, veinlets and stringers of ore are developed in the wall-rock parallel to the lode, but these are generally confined to a total width of less than one foot on either side of it (Plate XXXV). The contact between

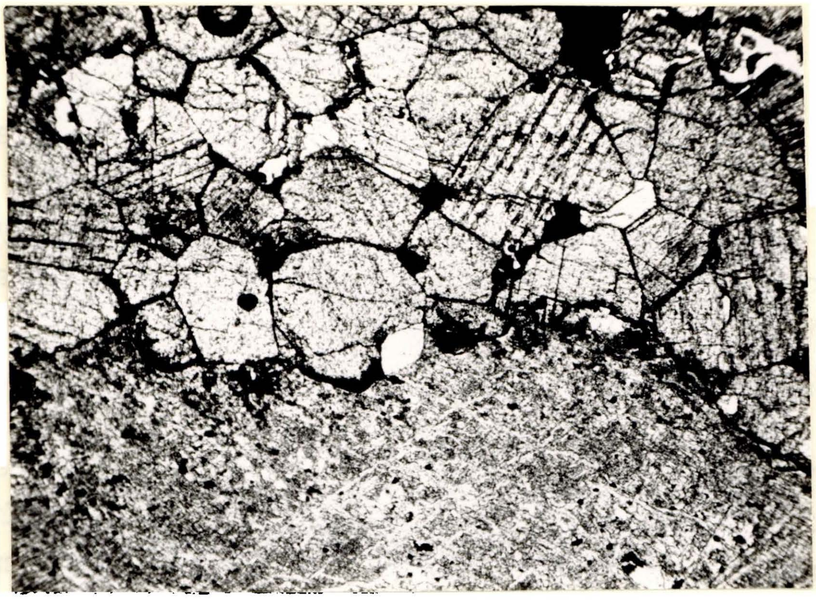

Plate XXXVI.- Contact between monazite ore and altered feldspathic wall-rock. Plane polarised light. x 32. 18143, Steenkampskraal.

ore-body and wall-rock is, in general, well defined (Plate XXXVI). An exception to this rule was first encountered at the eastern end of the outcrop. Here, disseminated ore occurs in altered granite over a width of some 13 feet, giving rise to a dark-coloured rock in which epidote is particularly well developed (16679, 16680). Development on the 300-foot level of the mine has revealed more mineralisation of this kind in patches; the ore is very well disseminated in both altered and unaltered wall-rock beyond the confines of the shear-plane, and is dressed with difficulty in the plant as a result of the toughness of the enclosing unaltered granite-gneiss. The frequency with which this type of mineralisation is encountered appears to increase with depth.

The sharpness of the contact between the ore-body and the wall-rock is otherwise characteristic, and, when viewed in thin section, is very striking, especially in the case of narrow stringers. This is especially true of the "phosphate ore" consisting of monazite, apatite and zircon; the metallic oxides and sulphides are in general better disseminated, and the replacement of the wall-rock by disseminated sulphide is very common.

The ore-body clearly truncates the granite-gneiss minerals, and their alteration products are concentrated along the contacts. In thin section, the contacts are somewhat scalloped and mamilliform. Xenoliths of country-rock in the ore are not uncommon near the contacts, and the ore often contains quantities of chloritic material in particular. Read's suggestion (1951, p. 12) that the ore-body may be "...at the same time a subtraction rock and a resister..." involved in the regional granitisation of the Archaean Complex, must therefore fall away in the light of this clear evidence for epigenetic emplacement.

That the emplacement and form of the ore-body has been controlled by pre-mineralisation faulting is quite definite. The ore-body has also been affected by post-mineralisation movements of different ages. The earliest of these occurred after the introduction of zircon and the phosphate minerals monazite and apatite. Thin sections show the brecciation of well-formed monazite and apatite crystals along the planes of movement, and the subsequent filling of the shear-zones by the metallic oxides and sulphides; the latter minerals form well-defined veins in the ore-body on a megascopic scale as well. Magnetite is especially prominent, and quartz is usually present. In this connection it might be added that the unbrecciated side of a shear is generally characterised by more iron than copper minerals, and the brecciated side by just the reverse. The shear-zones which carry sulphides also contain fragments of country-rock. These probably represent xenoliths originally present in the ore-body, and they may have provided planes of weakness along which shearing could take place.

Faulting later than the iron and copper mineralisation has affected the ore-body as a whole. Renewed movement along the original mineralised shear-zone has been partly responsible for the attenuation and eventual pinching out of a section of the ore-body on either side of the winze between the 100-foot and 200-foot levels; the magnitude of movement is, however, not so large that the traces of mineralisation are entirely obliterated. Minor strike-faults have also displaced the ore-body locally, and dip- and oblique-faults displace it a few feet from place to place. The most prominent of the latter is encountered in the inclined shaft and the 300-foot level west drive, striking SSE.- NNW. at a slight angle to the trend of the ore-body; the southern side of the fault is downthrown (see Fig. 6).

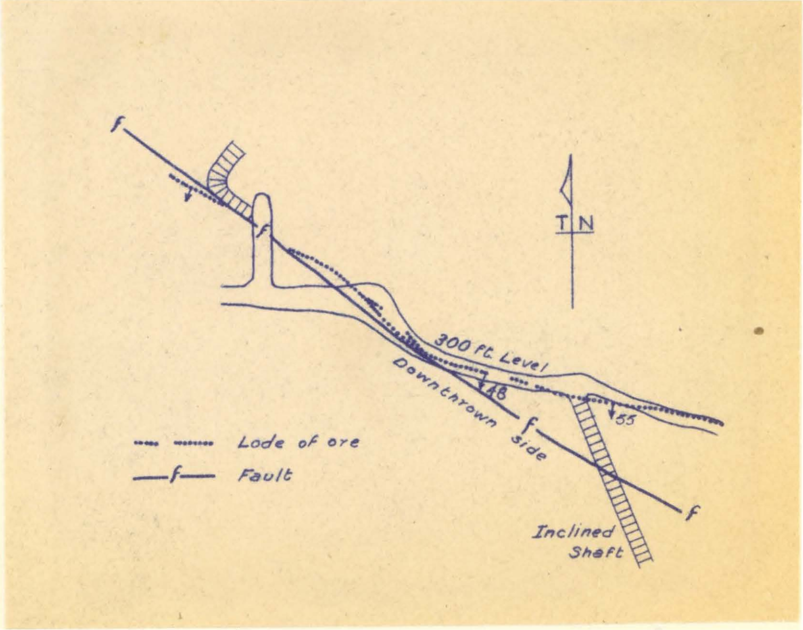

Fig. 6.- Post-mineralisation normal fault encountered on 300-foot level. The trace of the ore-body is drawn at the same altitude as the roof of the drive.

The fault-zone is filled by quartz, and the sheared granite-gneiss is replaced by recrystallised quartz, chlorite and talcose material. Minor strike-faults parallel to the major fault were frequently encountered during development. A quartz vein in the granite-gneiss near the fault contains calcite and fluorite; the latter mineral is also disseminated over a few feet in the granite-gneiss in the south wall of the drive.

The ore-body in this part of the mine has a variable thickness but is generally narrow, of the order of a few inches. As shown in Fig. 6, the lode bifurcates and encloses a horse of granite-gneiss; the lode-minerals have formed in a ferruginous breccia of pre-mineralisation age. The lode is somewhat discontinuous around the horse and the structure is difficult to visualize.

Between the 100-foot and 200-foot levels the dip of the shear-plane and of the ore-body flattens considerably, producing a distinct "roll", and then steepens again towards the 300-foot level. In general, however, the dip of the ore-body steepens to the west and flattens to the east. The "roll" is encountered at increasing depths westward, being near the 300-foot level in the westernmost portion of the mine (see Figs. 7 and 9).

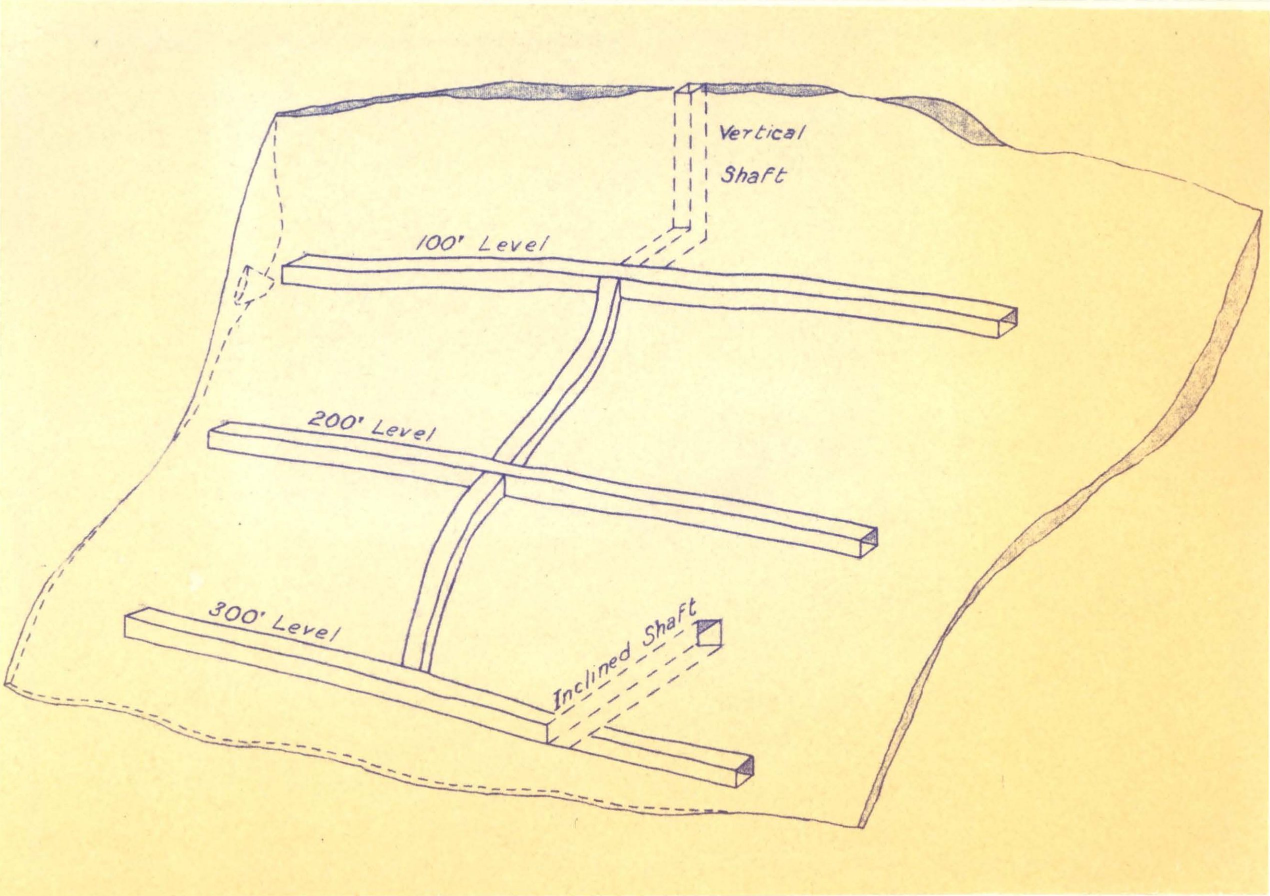

Fig. 7.- Diagrammatic representation of the skeleton layout of the mine, relative to the structure of the ore-body.

In the 100-foot level west drive, development proceeded until it eventually found itself surrounded by monazite ore. When wall-rock was again encountered, it was thought that a major dip-fault, which had abruptly truncated the ore-body, had been intersected. Development accordingly "turned left" (south) along joints and fracture planes (the supposed fault-zone) in the granite-gneiss, but was stopped after a few feet (see Fig. 8). The author could not find any criteria for a fault of such magnitude, since the characteristic brecciation of the granite-gneiss was especially conspicuous by its absence. It was suggested to the mine manager that development had actually proceeded through the contact of the ore-body into the wall-rock. Bearing in mind that the ore-body's strike on surface suddenly changes southwest at its western extremity, and that the foot-wall contact is typically altered and red, it was not surprising, therefore, when diamond-drill holes in the eastern wall of the drive encountered the ore-body again a few feet away. This proved that the drive had actually been developed through the foot-wall and not through a major dip-fault zone.

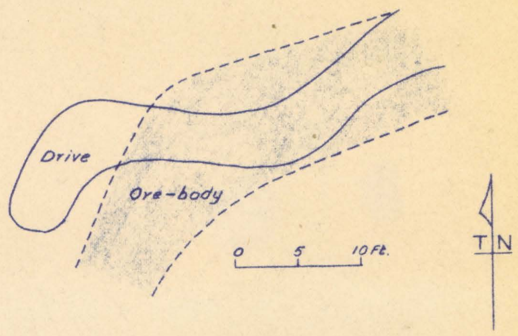

Fig. 8.- Diagram of the development at the western end of the 100-foot level west drive.

Between the 100-foot and 200-foot levels in the extreme western part of the mine, the ore-body splits into two branches, both of which dip southwards, with many parallel offshoots. In the western faces of the 100-foot level, the 200-foot level and the sub-levels between them, the main lode or lodes divide into stringers and pinch out. There is no reason, however, why continued development along the zone of shearing and alteration should not yield more ore after the manner of that encountered elsewhere in the mine.

The changes in strike of the ore-body along the 100-foot level west drive are accompanied by marked local steepening in dip of the shear-zone. The assay sheet (Map 6) gives the variation in dip as reported by the Anglo American Corporation during development. A "probable true dip" has been indicated as well on the strength of the author's own measurements, to compensate for the apparent erratic variation in the dip over short distances. The swelling and pinching of the main lode provides contacts which are not always strictly parallel to the actual dip of the ore-body; the inadvertent measurement of the dip of the contacts, therefore, has been responsible for the variation obtained. The variation in true width of the ore-body along the 100-foot level is also indicated in inches on the assay sheet.

It may be tentatively stated that the thickest development of ore is encountered at sudden changes in the dip or strike of the shear-plane. Theoretically such points would, through normal faulting and differential movement, afford a greater separation between the adjacent walls (cf. Bateman, 1955, p. 113, and Newhouse, 1942, p. 16). Considering, for example, the "roll" referred to, the differences in dip may well have accounted for the better mineralisation that has so far been encountered between the surface and the 100-foot level, and between the 200-foot and 300-foot levels, than between the 100-foot and 200-foot levels (see Fig. 9).

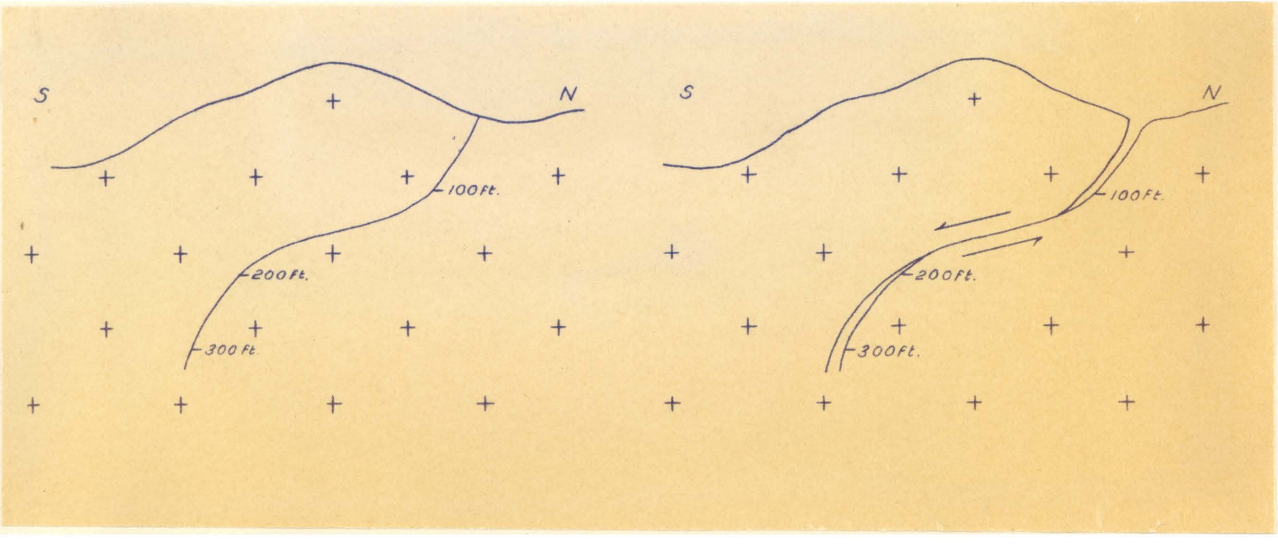

Fig. 9.- Ideal section of a widening shear-zone of the type encountered at Steenkampskraal.

Post-mineralisation movement has further served to accentuate the attenuation of the ore-body along the "roll", and although there is local brecciation and truncation of the ore-body here, no corresponding enlargement of the shear-zone elsewhere was observed; this could have been indicated by some other mineral infilling. The effect of widening of the shear-zone on the width of the ore-body would be reflected in lateral as well as vertical directions, and the greatest thickness of the ore-body viz. 30 feet, was encountered on the 100-foot level approximately 140 feet west of the cross-cut, where the strike of the shear-plane changes from east-west to ESE.- WSW.

The production of altered or hartschiefer bands in the shear-zone has resulted in a faint selectivity of replacement by the ore. This has given rise locally to a well-developed lamination or pseudo-bedding in the ore, especially near the contacts, where parallel veins and stringers in the wall-rock enhance the effect. Occasionally the laminations are marked by the development along them of thin coatings of white, yellow and green ochreous matter, which is possibly alteration material derived from the ore-minerals.

In the inclined shaft and the 300-foot level, the ore is ferruginous, compact and tough, and it is not readily crushable in the ball mill. The lode still dips southwards, and improves in thickness from a stringer in the east drive to a band 4 inches wide in the west drive. In the east it lies in red, highly sheared, banded hartschiefer-gneiss characterised by the presence of much magnetite and chlorite. The ore is well laminated and contains much ferruginous and chloritic alteration material. Euhedral chlorite, apparently pseudomorphous after magnetite, is developed in fractures or shear-zones. The ore-body is roughly parallel to the secondary foliation induced in the country-rock parallel to the shear-zone. Away from this zone of recrystallisation, however, the difference in dip between the ore-body and that of the granite-gneiss foliation is quite distinct.

2. Appearance and Texture of the Ore

The principal ore-minerals are monazite, apatite, zircon, magnetite, pyrite and chalcopyrite. Thin sections were cut from samples of the ore taken at intervals on the surface, from the 100-foot and 300-foot levels, and

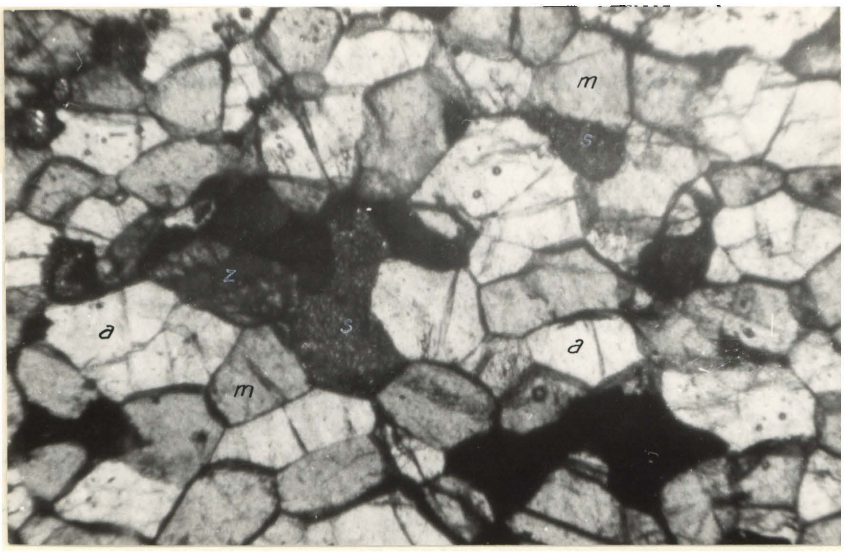

Plate XXXVII.- Average Steenkampskraal ore. Magnetite, opaque; sulphide (s), dark grey, finely stippled; zircon (z) grey, strong relief; monazite (m), light grey; apatite (a) white. Transmitted and reflected light. x 38. 18146.

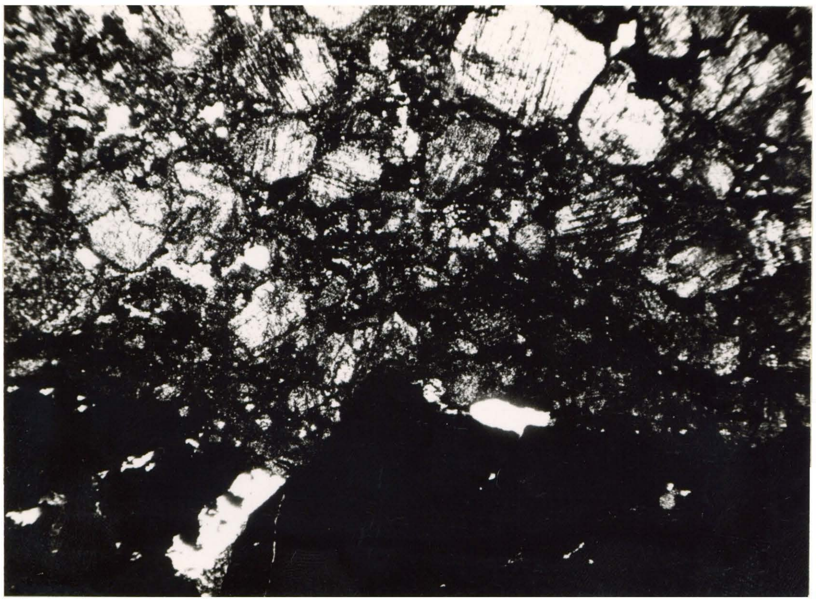

Plate XXXVIII.- Brecciated "phosphate ore" replaced along a shear by a vein and interstitial fillings of chalcopyrite (opaque). Plane polarised light. x 32. 18156, Steenkampskraal.

from diamond-drill intersections. The only significant differences in the sections made from the various localities are in the relative proportions of the constituent minerals. The oxidation of the metallic oxides and sulphides near the surface is also very apparent.

The numbers of the thin sections in which special features are well developed are given in the text; for the ore-body as a whole, the sections studied were the following:-

Surface: 16668-16679, 18137.

100-foot level: 17950-17952, 18116, 18117, 18138-18140, 18142-18147, 18149-18151, 18153-18157.

300-foot level: 19644.

Bore-hole intersections: 18503-18511.

(i) Colour. Macroscopically the ore is fawn to dark-brown in colour, depending on the quantity of secondary iron oxides present. Near the surface, secondary copper minerals impart greenish and bluish tints as well. On a weathered surface, the grains of monazite, covered by a veneer of black or brown limonitic material, often stand out in relief.

In thin section the ore is largely transparent, usually fawn in colour as the result of the preponderance of the phosphate minerals. Copper and iron minerals are opaque, but their respective pale-green and reddish-brown alteration products impart a dark colour to the thin section.

(ii) Granularity. The ore is phaneric. The "phosphate ore", represented by monazite, apatite and zircon, is equigranular (Plate XXXVII) except in rare instances of wall-rock replacement by these minerals. The grain-size of the "phosphate ore" averages 0.5 mm., but that of the quartz or the metallic oxides and sulphides is much more irregular. There is a tendency for all the ore-minerals to become equigranular in depth. Shearing which post-dates the phosphate mineralisation has resulted in brecciation of the ore, but this is generally restricted to one side of the shear-plane only (18156). Subsequent infilling by oxides and sulphides has taken place and they form a matrix about the broken grains (Plate XXXVIII). Irregular and rounded grains in the "phosphate ore" can be attributed to shearing and to replacement by younger minerals.

Plate XXXIX.- Monazite grains separated from the Steenkampskraal ore. -28 +32 mesh Tyler.

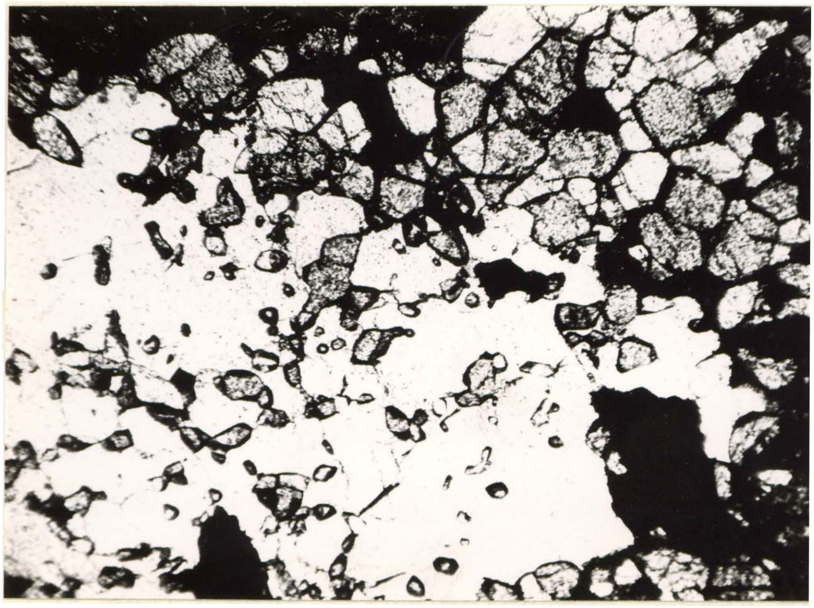

Plate XL.- Quartz replacing the "phosphate ore" and enclosing rounded relicts of monazite (grey) and apatite (white). Plane polarised light. x 32. 17947, Steenkampskraal.

(iii) Crystal Morphology. This characteristic varies in all the minerals, depending upon their mode of emplacement, alteration, replacement or paragenesis. Monazite usually shows the best crystal form. Crystal faces usually determine the outline of the basal sections, and the shape of crushed fragments is largely controlled by the excellence of the (001) parting and cleavages parallel to the c-axis.

In apatite, euhedral crystal forms are rare. Cleavage is absent, and the outline of the grains is controlled by parting perpendicular to the elongation of the crystals, by irregular fractures and sometimes by expansion cracks. It has been more readily replaced by younger quartz, and the metallic oxides and sulphides, than any other primary mineral.

Grains of zircon, which appears to be the mineral of earliest crystallisation, are all well rounded.

The metallic oxides and sulphides, interstitial to, or replacing the phosphate minerals, or disseminated in the wall-rock, are usually irregular in crystal form. They are anhedral, rarely subhedral, as a result of their later emplacement. Their truncation and partial replacement of the earlier-formed minerals cause the latter to be anhedral as well.

3. Constituent Minerals

(a) Monazite

(i) Grain-size. Grain-size varies from less than 0.1 mm. to 1.5 mm., but a fairly constant average size of $\pm$0.5 mm. is maintained (see Plate XXXIX). In the crush-zones the original grains have been brecciated. The resultant smaller fragments are not highly angular as might be expected, but are generally equant, being bounded by cleavage planes, or rounded by solution and replacement by the later oxides, sulphides and quartz, for which the brecciated zones have provided channelways (see Plate XXXVIII). The rounded relicts of monazite in quartz veins which replace the ore, are very striking; the grains decrease in size from the walls to the centre of the veins, and suspended as they are in the quartz, give the impression of having been "stoped" from their original positions (see Plate XL).

(ii) Crystal Morphology. Monazite is the only euhedral mineral, and in the unreplaced "phosphate ore", the crystal faces of adjacent monazite crystals, apatite grains, or monazite and apatite grains match perfectly, subject to the original order of crystallisation and the habit of early-formed individuals (see Plate XLI). The subsequent introduction of oxides, sulphides and quartz has usually separated the phosphate grains from each other to some degree, but the original texture can be visualized quite easily (see Plate XLII). More frequently, where the later mineralisation has rounded the grains or replaced them in part along cleavage and fracture-planes, and along their crystal-faces, monazite is subhedral or even anhedral. When bounded by well-developed crystal-faces, the grains are equant. There is, however, a tendency in some grains towards elongation in the direction of the c-axis (see twinned crystal in Plates XLIIIA and XLIIIB).

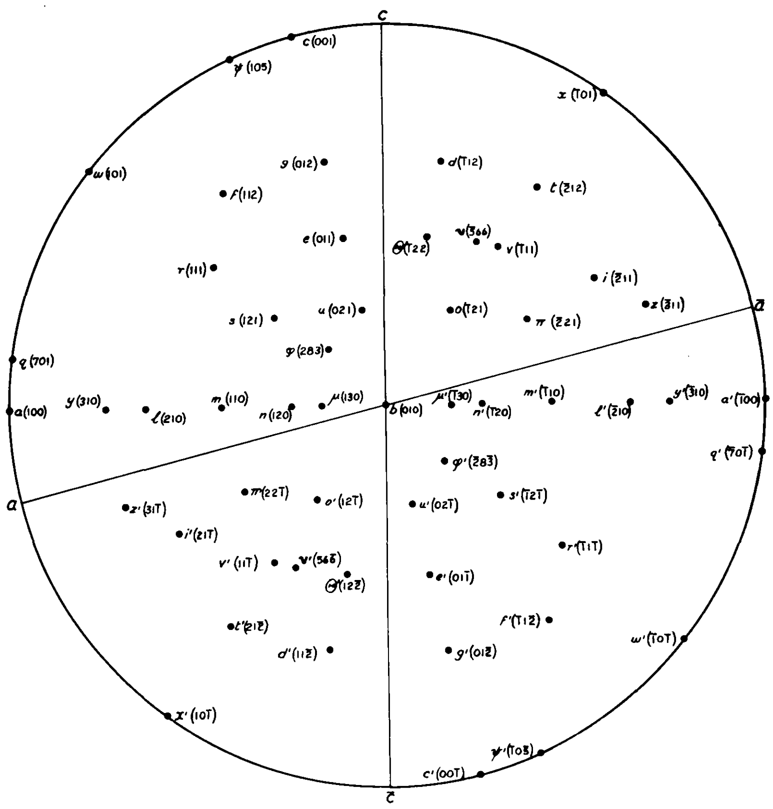

Fig. 10.- Stereographic representation of all the crystal-faces of monazite recorded in the literature. Stereogram parallel to (010).

Plate XLIIIA.- Polysynthetically twinned monazite, first position. Crossed nicols. x 32. 16670, Steenkampskraal.

Plate XLIIIB.- Polysynthetically twinned monazite, second position. Crossed nicols. x 32. 16670, Steenkampskraal.

In order to assign Miller indices to the crystal-faces and to the cleavages which would probably be parallel to them, a separate stereographic projection (Fig. 10) was made of all the crystal-faces of monazite recorded by Palache, Berman and Frondel (1951, p. 692), Hintze (1897, pp. 295-296) and Rosenbusch and Mügge (1929, p. 436). The projection has been made parallel to (010) instead of perpendicular to the c-axis as is conventional. The reason for this will be immediately apparent when the scattering of the poles of the cleavages is seen in Fig. 11, and any attempt is made to orient them relative to the crystallographic axes.

(iii) Cleavage. Parting and cleavage in individual grains were determined on the Universal Microscope Stage, and plotted stereographically relative to the vibration directions of the α-, β- and γ-rays (Fig. 11).

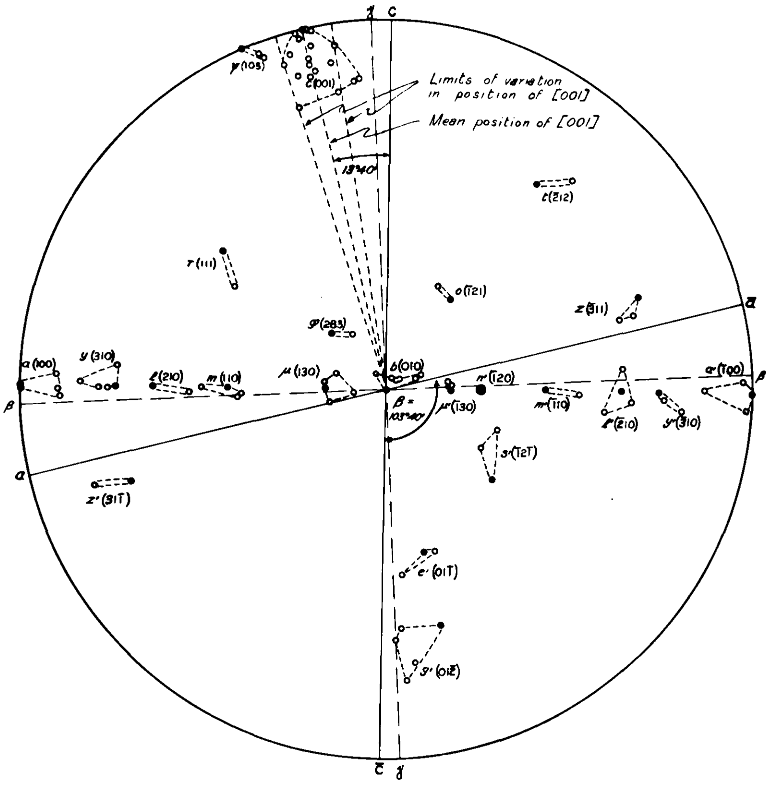

Fig. 11.- Stereogram of cleavages in monazite; projection parallel to (010). Data from literature indicated as solid lines and circles. Data obtained by measurement indicated as dashed lines and open circles.

In order to identify the cleavage-planes, the mean position of either the *a*(100) or the *c*(001) cleavage must be established. Assuming $\beta = 103°40'$ * (Palache, Berman and Frondel, 1951, p. 691), the crystallographic c- and a-axes can then be drawn on to the stereogram, and the variation in the γ.c angle measured. On a stereographic projection perpendicular to the c-axis, the poles of the (001) cleavage would fall along small circles near the centre of the stereogram, and the establishment of the mean position of [001] would be much more difficult. To ensure greater statistical accuracy in establishing the mean [001] position, all the $(00\bar{1})$ poles were transferred to the corresponding (001) positions.

The development of perfect parting parallel to (001) is most striking. As will be seen from the stereogram (Fig. 11), the principal cleavages are developed parallel to the c-axis, and are *a*(100), *y*(310), *l*(210), *m*(110), *n*(120), μ(130), and *b*(010). The other cleavages are parallel to ψ(105), *r*(111), φ(283), *o*$(\bar{1}21)$, *t*$(\bar{2}12)$, *z*$(\bar{3}11)$, *s*(121), *e*(011), and *g*(012).

The scattering of the poles of the cleavage-planes about the ideal positions is attributed partly to the limitations of the method employed to measure them, and partly to physical distortion of the crystals by shearing and compressive forces. Cleavage-planes have been displaced relative to parting-planes, and the development of parting in the monazite seems therefore to be related to stress acting upon the already crystallised mineral.

(iv) *Crystal-faces*. Crystal-faces are present on all the grains unaffected by later mineralisation. The individual grains are, however, too small to mount on a two-circle reflecting goniometer, and the crystal-faces were therefore measured in thin section on the Universal Microscope Stage and were plotted stereographically in the same way as the cleavages (see Fig. 12).

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* Ford (1945, p. 700), Rosenbusch and Mügge (1929, p. 436) and Hintze (1897, p. 294), quoting E.S. Dana, give the complement of this angle *viz*. $\beta = 76°20'$. The modern usage, however, seems to require the obtuse and not the acute angle (Palache, Berman and Frondel, 1946, p. 16).

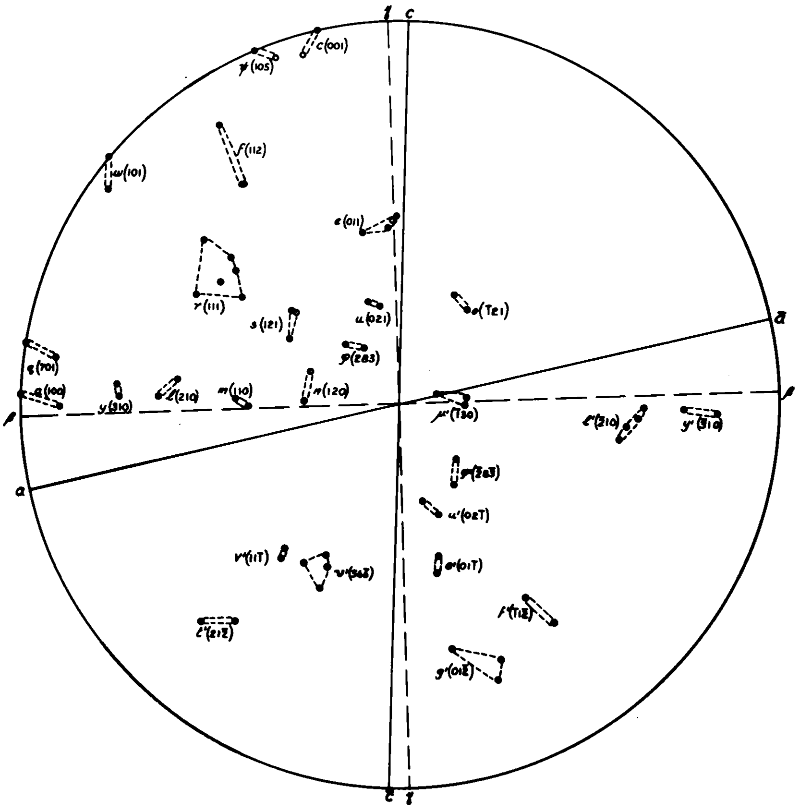


Fig. 12.- Crystal-faces on monazite, stereographic projection parallel to (010). Data from literature indicated as solid lines and circles. Data obtained by measurement indicated as dashed lines and open circles.

The limitations as regards accuracy which applied to the plotting of the cleavages apply equally well here. Seeing that a small portion of a crystal-face and not a cleavage-plane is being considered, the inaccuracy is probably greater. For this reason the γ.c-angle has been measured on the cleavage stereogram and not on the crystal-face stereogram.

Comparison of the positions of the poles of the crystal-faces with those on the idealised stereogram (see Fig. 10) shows the following faces to be developed:-

a(100), y(310), l(210), m(110), n(120), μ(130), c(001), ψ(105), w(101), q(701), r(111), f(112), e(011), s(121), φ(283), u(021), o($\bar{1}$21), t($\bar{2}$12), g(012), v($\bar{1}$11), and ν($\bar{5}$66).

No b(010) face was recognized. The number of pyramidal faces that are developed is probably responsible for the equant nature of the monazite crystals.

(v) Twinning. Polysynthetic twinning occurs with (001) as composition-plane and [001] as the twinning-axis. This, according to the previously quoted mineralogical literature, is a very rare phenomenon, the common twins being developed parallel to (100) and more seldom parallel to (201) and $(\bar{9}02)$ (Hintze, 1897, p. 296). Hintze (1897, p. 348), quoting A. Lacroix, describes lamellar twinning parallel to (001) in monazite of pegmatitic origin from Vohitrambo, Madagascar. The crystals are about 10 cms. in size, and the twinning is probably secondary in origin. Quoting O.B. Böggild, he also describes monazite crystals about 4 mm. in size which contain thin twin-lamellae throughout, parallel to (001), and which are visible to the naked eye. This monazite is from a quartz pegmatite at Kekertak in the Upernivik District of Greenland; no explanation for the twinning is offered (Hintze, 1897, p. 365).

In the Steenkampskraal monazite the twin-lamellae are usually fine but can be coarse, and number from about five upwards in any grain (see Plates XLIIIA and XLIIIB). A common feature is the relative displacement of cleavage-planes by twinning-planes as shown in Fig. 13, indicating that the twinning, like parting, is definitely a secondary feature.

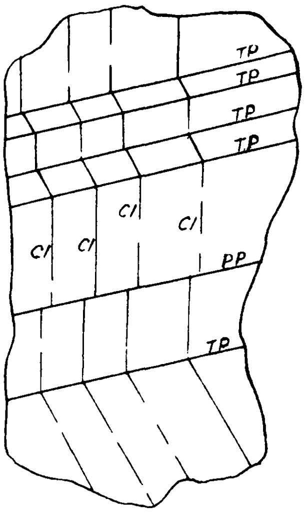


Fig. 13.- Diagrammatic representation of the effect of twinning and parting on cleavage in a monazite crystal. TP twinning-plane, PP parting-plane, Cl cleavage-plane.

The twin elements were determined on the Universal Microscope Stage in the same way as were the crystal-faces and the cleavage-planes, and are represented in Figures 14 and 15.

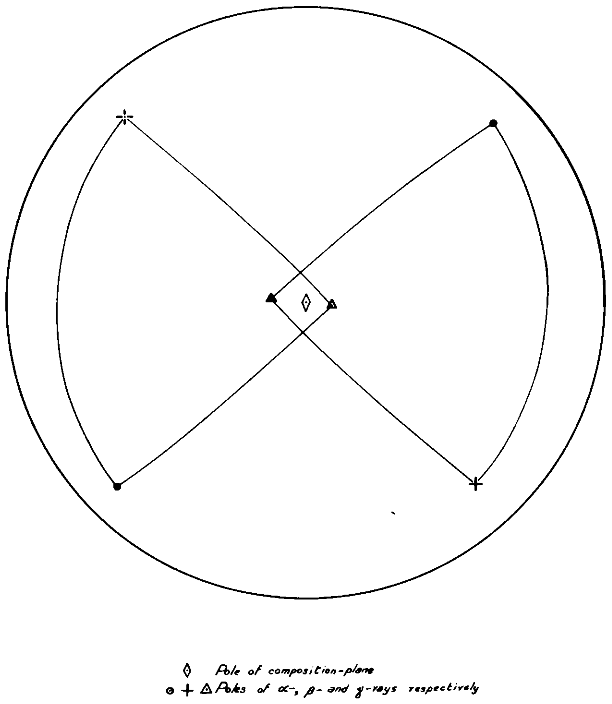


Fig. 14.- Symmetry of the polysynthetic twin in monazite. Stereographic projection parallel to (001).

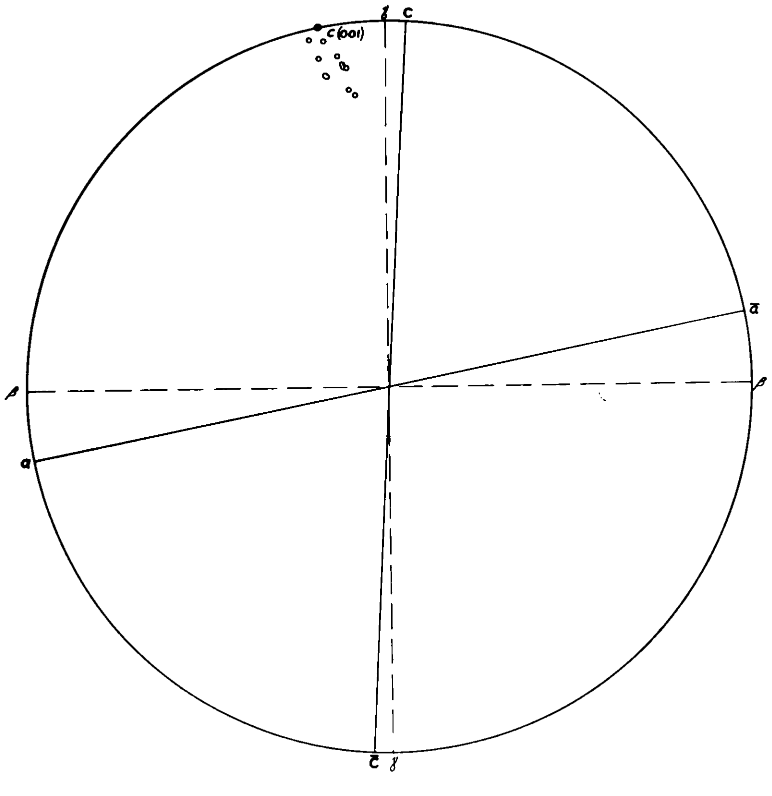


Fig. 15.- Composition-planes of polysynthetic twins in monazite; stereographic projection parallel to (010). Data from literature indicated as solid lines and circle. Data obtained by measurement indicated as dashed lines and open circles.

Twinning- and cleavage-planes in the monazite become less common with increase in depth, and distorted and discoloured grains are rare, except where stress has been active. Twinned crystals are often found in association with distorted grains which show purplish discolouration, and occasionally undulose extinction as well. It seems possible that the twinning took place as a result of stresses which prevailed during shearing, but twinned crystals are not necessarily associated with shear- or crush-zones.

Twin-lamellae are sometimes impregnated to different degrees by secondary iron oxides; where replacement of this nature has taken place, the lamellae no longer extinguish or illuminate properly between crossed nicols.

In order to establish any relationship between the orientation of the twinning-planes, parting-planes and the plane of post-mineralisation shearing, a petrofabric diagram of the poles of twinning- and parting-planes was prepared from an orientated thin section in which they were particularly abundant (17952). The resultant fabric is shown in Fig. 16; the girdle of poles in the (a-c) plane

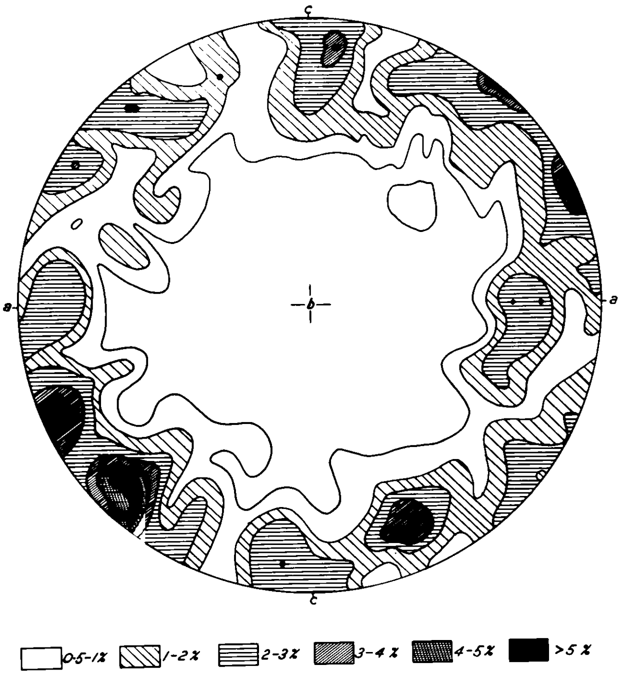


Fig. 16.- Petrofabric diagram of the poles of 185 twinning-planes and 80 parting-planes in Steenkampskraal monazite (17952). Plane of post-mineralisation shearing, a-b; direction of movement as indicated by slickensides, a-a.

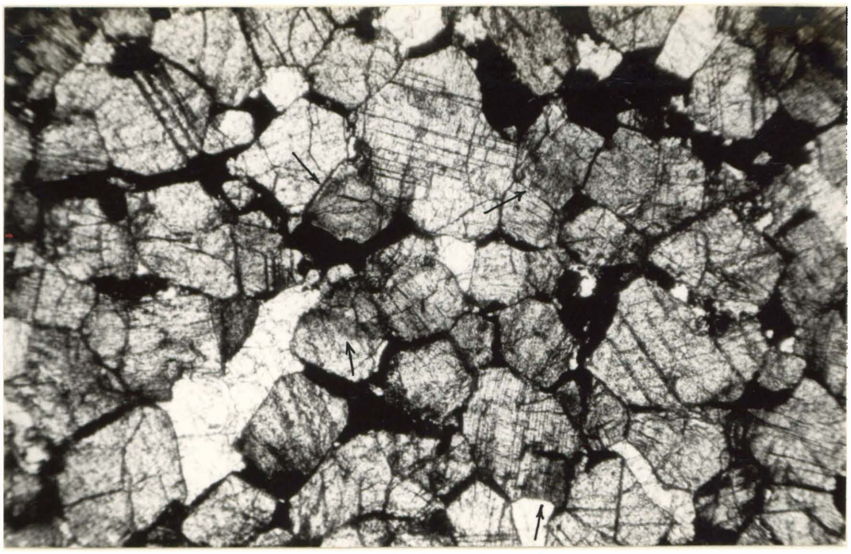


Plate XLIV.- Discolouration in deformed monazite crystals (arrows). Plane polarised light. x 32. 18157, Steenkampskraal.

i.e. perpendicular to the plane of shearing and in the same plane as the direction of slickensiding, is at once obvious. Most of the planes are slightly oblique to the plane of shearing, as might be expected, but none are near-vertically inclined to the (b-b) direction. This must be accepted as confirmatory evidence for the secondary and imposed nature of the twinning and parting phenomena in the crystals.

The actual process involved is probably that of twin-gliding as postulated by Buerger (1945, pp. 478-479) and Bell (1941, pp. 247-261). The slip-plane here has simple indices (001) and the twinning-axis [001] is normal to it. The molecular, atomic or ionic reconstitution of the monazite from the untwinned to the twinned form is broadly related to stresses imposed on the mineral during shearing; whether recrystallisation of the sort considered by Buerger and Washkin (1947, pp. 296-308) is valid in this instance, however, is uncertain.

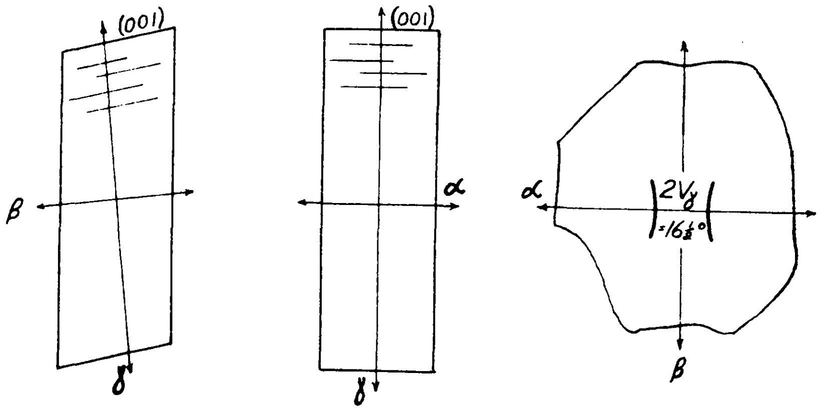
(vi) Specific Gravity. The specific gravity of the monazite was determined by the pyknometer method, using the same purified flotation concentrate that was submitted for chemical analysis. Most of the material was very fine-grained, and the surface tension of the water prevented a good deal of it from becoming properly wet, so the determination was done in alcohol. The average specific gravity, from the nearest four of six separate determinations, is 5.12 ± 0.02.

(vii) Colour. Viewed through a pocket lens or binocular microscope, the monazite is normally pale amber or honey-yellow in colour, and perfectly transparent. Impregnation along cleavage-planes or fractures by secondary ferruginous matter, or a similar coating on the grains, may render them very much darker, however, and even subtranslucent.

In thin section the monazite has a pale-fawn colour and is nonpleochroic. Its relief is high and it stands out readily from neighbouring minerals even when highly altered. It is easy to detect between crossed nicols, as it shows interference colours up to Third Order in prismatic section, the maximum retardation $n_\gamma - n_\alpha$ being observed in sections parallel to (100) (see Fig. 17). Basal sections display very weak birefringence.

Occasional grains show a purplish discolouration which has the appearance of a shadow in the crystal, by plane polarised light (see Plate XLIV). This feature is often accompanied by undulose extinction. It is more generally observed and better developed in grains showing the distinct distortion of cleavage- and twinning-planes, and expansion cracks radiating from interstitial minerals of later introduction. The discolouration is therefore probably due to physical disruption of the crystal structure. Grains which have been subjected to shearing, however, may become severely brecciated, and yet show discolouration in only a few instances.

(viii) Optical Orientation. The α-ray vibrates parallel to the crystallographic b-axis. The $\gamma.c$-angle was measured from the stereogram of cleavages (see Fig. 11) assuming from literature that $\beta = 103°40'$. For the mean position of the (001) pole, $\gamma.c = 3°00'$, but it may vary from +1°15' to -7°30', as the stereogram indicates.



Section // (010)
$n_\gamma - n_\beta = 0{\cdot}048$

Section // (100)
$n_\gamma - n_\alpha = 0{\cdot}049$

Section // (001)
$n_\beta - n_\alpha = 0{\cdot}001$

Fig. 17.- Optical orientation of monazite.

(ix) Refractive Indices. The refractive indices were determined by the immersion method on an ordinary microscope stage, using a source of Na_D light and high refractive index melts of yellow phosphorus, sulphur and methylene iodide as described by West (1936, pp. 245-249). n_α and n_β were measured in basal sections, and n_γ in prismatic sections (see Fig. 17).

The angle of minimum deviation (δ) of every liquid mixture used for a determination was measured on a goniometer, a drop of the liquid being held in a hollow prism. The refractive index of the liquid (N) was then read off from a graph of δ vs. N for Na_D light. By repeating the process with successive immersions in liquid mixtures, the refractive indices of which varied by a few digits in the fourth decimal place, the index for the γ-ray, say, was approached and then passed. The exact figure for the index could then be ascertained with a very small margin of error. Control measurements were made to establish the margin of error caused by evaporation, change in room temperature etc., and a variation of ± 0.0003 is adequate to cover any error so incurred. It was found that all the refractive indices were lower in monazite impregnated by secondary iron oxides. Fragments which were as free as possible from such contamination were chosen for measurement.

For the measurement of n_β, basal sections must be employed. In an ideal (001) cleavage fragment, the α-ray vibrates parallel to the cleavage-plane and its index can be measured directly, but this is not the case with the β-ray. The maximum angle for $\gamma.[001]$ from the cleavage stereogram is 15° (see Fig. 11), and this is equivalent to the angle $\beta.(001)$ in the cleavage fragment. If the β-ray is not parallel to the cleavage-plane, therefore, a positive error is introduced into the determination which reaches a maximum of +0.0093 for the angle of 15°. This figure was derived from a graphical construction of the β-γ wave-surface. To avoid this error, the author chose sections in which the interference figure was properly centred, and the lowest figure obtained for n_β from a number of determinations was accepted.

For the measurement of n_γ, prismatic sections with outlines determined by parting and cleavage were chosen, and the highest value obtained was accepted as correct.

The refractive indices of the monazite are as follows:-

$n_\alpha = 1.7846 \pm 0.0003$

$n_\beta = 1.7858 \pm 0.0003$

$n_\gamma = 1.8338 \pm 0.0003.$

(x) Optic Axial Angle. Attempts to measure the optic axial angle on the Universal Stage met with no success, as no illumination could be obtained between the optic axes to establish their position accurately. The Mallard method was adopted instead, using a specially cut basal section of aragonite, which has an optic axial angle of 18°, as constant.

The optic axial angle so obtained for the monazite is $2V_\gamma = 16°22'$.

Calculation of the optic axial angle from the refractive indices, using the equation

$$\tan^2 V_\gamma = \frac{\frac{1}{\alpha^2} - \frac{1}{\beta^2}}{\frac{1}{\beta^2} - \frac{1}{\gamma^2}}$$

gave $2V_\gamma = 19°52'$.

(b) Apatite

Apatite occurs interstitially to monazite, usually in less idiomorphic crystals; a few grains are subhedral to euhedral, but the majority are anhedral (Plates XXXVII and XLII). The proportion of apatite to monazite is far from constant, but grain-counts for all portions of the ore-body show that the two phosphates together invariably form a total of ± 80% of the ore. The proportion of apatite tends to increase with depth.

The grain-size varies proportionately with that of the monazite, the average size being about 0.4 mm. and therefore slightly less than that of the monazite. When apatite is present in excess of monazite, however, coarser development is observed, and the grain-size exceeds that of even the best-developed monazite (18510). Isolated euhedral crystals occasionally occur some distance into the altered wall-rock, beyond the boundaries of disseminated monazite; this might suggest a greater mobility for apatite prior to crystallisation.

Apatite grains which enclose small crystals of monazite (16669) indicate that the apatite is the younger of the two minerals.

Poorly-developed cleavage has occasionally been observed parallel to the length of the crystals. Far more common is an imperfect to perfect parting at right angles to this direction. Irregular fractures are common. Radiating expansion cracks and undulose extinction have been brought about in the apatite by the interstitial introduction of later primary or secondary minerals, or by their impregnation of adjacent monazite crystals.

The optical properties are perfectly normal and characteristic of apatite. The refractive indices were measured by the immersion method, using white light, and gave $\omega > 1.631 > \varepsilon$, which indicates a fluorapatite.

Fractures and partings very seldom contain the ferruginous matter so often found in monazite; the apatite is, therefore, generally very clear relative to the monazite. Where the ore has been veined or replaced by quartz, apatite has been replaced to a far greater degree than has the monazite. Numerous rounded inclusions of monazite are found in the quartz, but very few of apatite, and these are of much smaller dimensions.

(c) Zircon

Zircon is an accessory constituent of the "phosphate ore", and is encountered as isolated individuals interstitial to monazite and apatite (Plate XXXVII). It occurs most frequently on or near the contact between the "phosphate ore" and the altered wall-rock, and also at the extremities of the stringers which probe the wall-rock. The zircon apparently crystallised first, because it is sometimes enclosed in large apatite or monazite crystals (16668, 18503), or tightly surrounded by the other minerals without any evidence of replacement or fracturing in the latter. Zircon has in rare cases been replaced by apatite.

The grains are usually smaller than those of the phosphate minerals, but in some instances are just as well developed. Grains that were separated from outcropping ore are markedly oval or spherical; idiomorphism is more common in depth, and subhedral to euhedral grains occur. The rounded form of the crystals may be due to resorption prior to the crystallisation of the phosphates.

The zircon grains are usually zoned, often strongly so (18504). No cleavage was observed; irregular fractures, sometimes radiating from the centre, are present. Concentric cracks are also evident. Secondary ferruginous matter in the cracks and fractures gives the zircon grain, as a whole, a dark colour. Extinction is sometimes undulose, indicating the effect of post-crystallisation pressure on the grains, and the cracks no doubt result from this

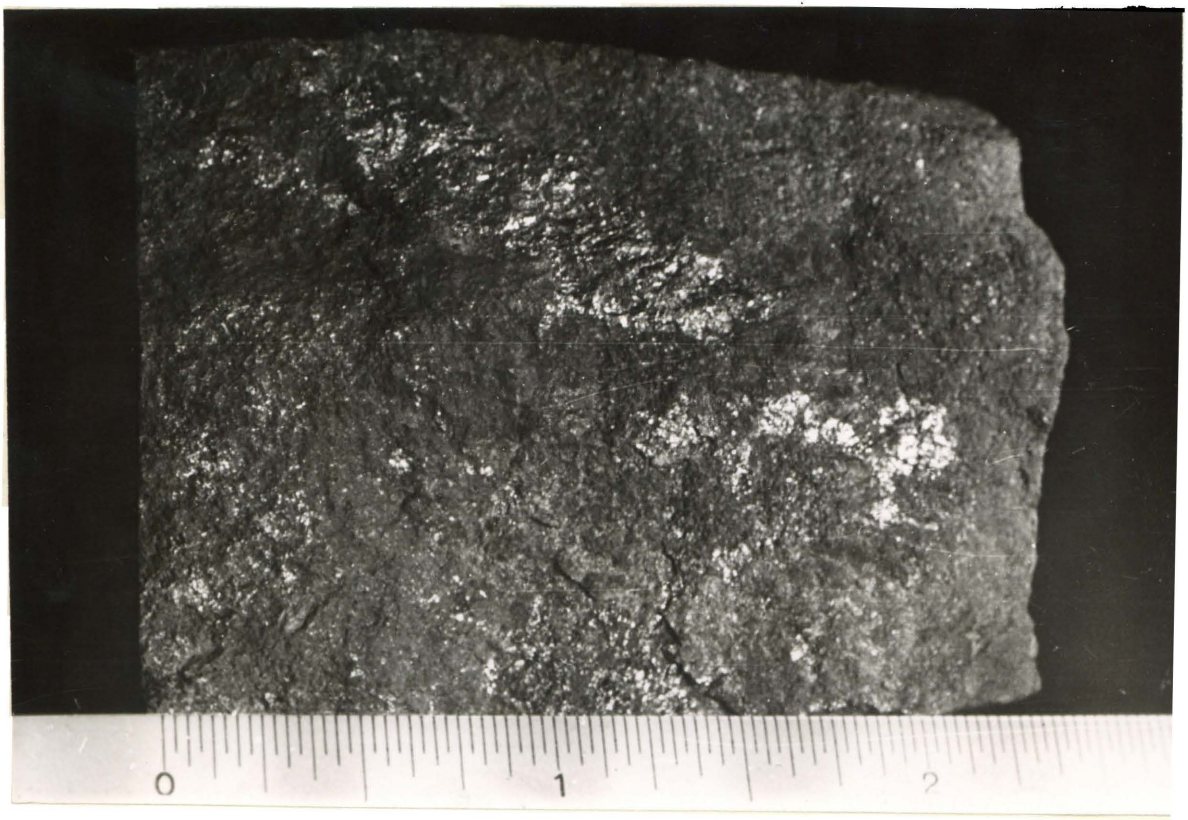


Plate XLV.- Coarse development of chalcopyrite (light-coloured) in granular phosphate ore (dark-coloured). Steenkampskraal. Scale in inches.

Grain-counts indicate that the percentage of zircon in the ore decreases slightly with depth.

(d) Copper- and Iron Sulphides and Iron Oxides

The oxides and sulphides occur similarly and appear to have been introduced into the ore-body at the same time, and will therefore be described together.

They occur as follows:-

(i) Interstitially to the phosphate minerals (Plates XLI, XLII, XLIV, XLV);

(ii) Disseminated in the wall-rock;

(iii) Filling brecciated zones in the ore-body (Plate XXXVIII);

(iv) Directly associated with veins or bodies of quartz which replace the ore.

The primary oxide is magnetite, and the primary sulphides are pyrite, chalcopyrite and galena. All these minerals are associated with each other throughout the ore-body, except galena, which is present in very subordinate amounts, and then associated only with chalcopyrite (polished section D.P. 100). The secondary oxides are haematite, limonite and leucoxene.

Careful observation reveals the following reaction series:-

$$\underset{Fe_3O_4}{\text{Magnetite}} \rightarrow \underset{FeS_2}{\text{pyrite}} \rightarrow \underset{CuFeS_2}{\text{chalcopyrite}} \rightarrow \underset{CuS}{\text{covellite}}$$

Magnetite is replaced by pyrite (18509), pyrite by chalcopyrite (18156, 18503), and chalcopyrite by covellite (18151: polished section 18504). The textures are very simple, being most often of peripheral replacement of the mineral grain. Chalcopyrite occasionally replaces pyrite, developing from the centre outwards (polished section 18503). The monazite ore unfortunately takes a very poor polish, and the possible alteration of these minerals to α-chalcocite was not observed under the microscope. The replacement textures correspond in part to those described by Newhouse (1928, pp. 155-156) and Bastin (1950, p. 52) for preferential replacement of ore-minerals.

The chemical composition of the members of the series indicates that the replacement of an earlier by a later mineral is due to enrichment in Cu^{++} and $S^{=}$. These minerals may or may not be regarded, therefore, as secondary in nature; those which are definitely secondary, however, are azurite, malachite and chrysocolla.

The grain-size of the oxides and sulphides varies considerably, and the shape of the grains is very irregular as a result of crystallisation in confined spaces. The phosphate minerals have been replaced by the oxides and sulphides to a variable extent, resulting in the often highly rounded grains of apatite and monazite in a matrix of oxide or sulphide. In places a film of oxide or sulphide exists between the adjacent crystal-faces of the phosphate minerals. The grains of the metallic minerals are rarely euhedral; those in the quartz bodies are generally rounded, possibly due to resorption before final crystallisation of the quartz. Euhedral cubes of pyrite were observed, however, in the quartz from diamond-drill intersections (18504). The latter feature leaves no doubt, therefore, as to the origin and mode of introduction of the oxides and sulphides. Furthermore, the sulphides frequently form a contact-zone between the quartz and the older rock, a feature which substantiates their introduction by siliceous solutions (18504).

In its replacement of the wall-rock, magnetite displays preference for micaceous zones consisting of partially altered biotite. Its introduction has caused some recrystallisation of the mica, which exhibits spherulitic and minor flow features. The magnetite is frequently altered to haematite, limonite and whitish opaque matter. To determine the identity of the latter, fresh magnetite was separated from a heavy fraction of the crushed ore, and was tested for titanium by the hydrogen peroxide method. The result was positive, and the alteration product is therefore most likely leucoxene. It occurs as massive aggregates in somewhat irregular association with the altered magnetite, but also along distinct octahedral planes in the magnetite itself. It has commonly spread beyond the confines of the original magnetite into adjacent minerals.

The haematite is usually earthy and reddish-brown in colour, but bright-red scales are often developed near the surface. The haematite and limonite are distributed throughout the ore-body, and the ferruginous nature of parts of the wall-rock can no doubt be attributed to concentrations of these minerals. The alteration of the magnetite underground is slight by comparison with that on surface, but there are sections of the ore-body that contain much secondary ferruginous matter as a result of this alteration. Where decomposition is advanced, the secondary minerals form the matrix between the phosphate grains. The susceptibility of monazite to impregnation by secondary iron minerals along cleavage-planes, parting-planes, twinning-planes and cracks, is very marked.

The secondary copper minerals azurite, malachite and chrysocolla are distributed in the ore-body, wall-rock and country-rock from the 100-foot level upwards. Chrysocolla is found mainly in the trenches at the surface, but the other two minerals persist to greater depth.

Covellite is comparatively rare in the ore-body, but was nevertheless observed in ore from diamond-drill intersections below the 300-foot level, which indicates a wide vertical distribution.

Local banding of the copper minerals in the ore-body parallel to the contacts has been brought about by differences in the intensity of oxidation of the primary sulphides, represented predominantly by the alteration of chalcopyrite to covellite and chalcocite. This banding takes the form of zones and lenses of secondary sulphides alternating with the primary minerals. The effect is enhanced by less well-defined bands of ferruginous alteration products. In thin section the impregnation of monazite by ferruginous material in the vicinity of covellite is often distinct, and would seem to be due to the release of iron during the formation of covellite from chalcopyrite (18506: polished section 18504).

Chalcocite is irregular in its distribution. It occurs in very fine-grained, earthy masses distributed locally in the ore and wall-rock, and especially along cracks and fractures. It was identified as α-chalcocite by X-ray diffraction.

The oxide and sulphide minerals, except for chalcocite, were identified in polished sections, and all their properties were found to be characteristic. Reference to thin sections cut from the same samples enabled these minerals to be recognized by reflected light in all the thin sections that were studied.

Chemical analyses of the ore from four different diamond-drill intersections show gold to be present in

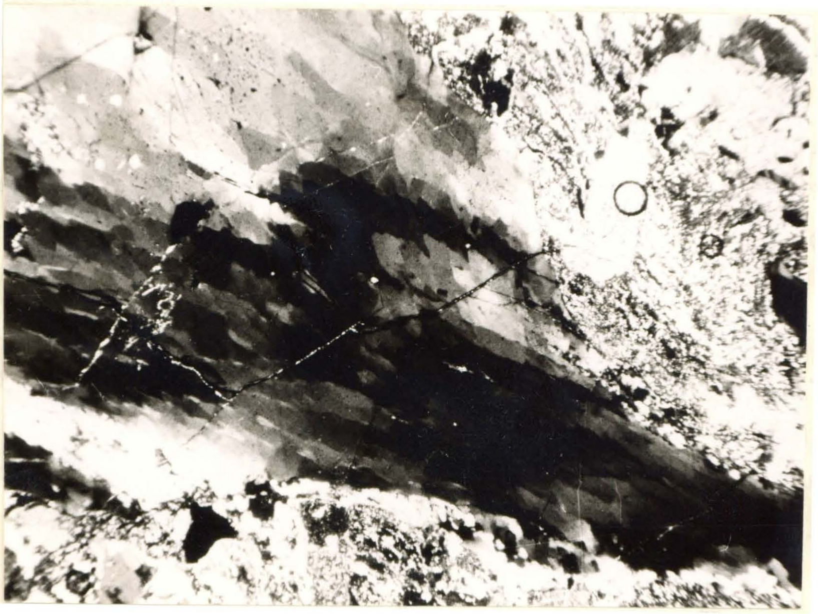


Plate XLVI.- Linear recrystallisation of quartz in a post-mineralisation vein. Crossed nicols. x 32. 16681, Steenkampskraal.

distinct amounts (see Table No. 6), but it was not observed by the author in any of the thin or polished sections, or in the ore-body itself.

(e) Quartz

This mineral occurs in veins and vein-like bodies which replace the ore and the wall-rock mainly parallel to the pseudo-stratification of the ore-body.

Truncation of the phosphate minerals is very distinct and results in very clear-cut contacts, which are somewhat scalloped or botryoidal where the quartz bodies become thinner. Where the phosphate minerals have been "stoped out" or partially replaced by the veins, the grains of monazite and apatite appear as rounded inclusions in the quartz, decreasing in size away from its contacts (Plate XL). Large inclusions comprise phosphate crystals still adjacent to each other.

Microscopic inclusions, some in streaks and stringers, occur throughout the quartz. Their outlines may be quite irregular, but some are spheroidal and might be drops of liquid. Their refractive indices are both less than and greater than that of quartz, and some are highly birefringent. Some possibly represent remnants of the replaced phosphate minerals.

The grain-size of the quartz is very irregular. The coarse grains are generally intergrown with much finer grains between them. Some grains have normal undulose extinction. More commonly, however, the coarse grains are composed of many finer fragments fritted together; these give the impression of undulose extinction in the grain as a whole, whereas sympathetic extinction of similarly orientated fragments is actually taking place. These fragments extinguish linearly (see Plate XLVI), indicating that they are recrystallisation features, and that recrystallisation has taken place as a result of definite directional stresses. These stresses probably accompanied the post-mineralisation shearing of the ore-body in directions more or less parallel to its strike.

More tangible effects of this shearing may be observed in inclusions of monazite in the quartz, which now appear as elongated augen of irregular length and breadth, but which have a common direction of lineation. Elongated lenticles and streaks of sulphide particles, on the other hand, occur in directions oblique to that of the linear recrystallisation in the quartz. Besides these inclusions of ore, the quartz bodies also contain xenoliths of wall-rock which exhibit similar features.

Some of the quartz veins, notably those at the present ground surface, have not been affected by recrystallisation, and may be of a younger age. They are generally narrow, and have comb structure about a simple mosaic of fine crystals at the core. The veins sometimes display chilled margins of fine crystals. They are often shattered and impregnated by ferruginous material.

(f) Siderite

Thin veins of siderite occur in the ore-body in exactly the same manner as they do in the altered wall-rock.

4. Sequence and Age of Mineralisation

(a) Paragenesis

1. The faulting or shearing which paved the way for later mineralisation, took place in the already rigid crystalline complex. In the immediate vicinity of the differential movement, brecciation and recrystallisation of the granite-gneiss took place to varying degrees. This was followed by hydrothermal alteration of the greater part of the granite-gneiss thus affected.

2. Into the resultant aggregate of altered feldspars, altered micas, altered metallic minerals, quartz and secondary quartz, the minerals constituting the "phosphate ore" were introduced. They crystallised in the order zircon, monazite and apatite, as indicated by their mutual relationships. Selective replacement of the altered granite-gneiss is reflected in the pseudo-stratification of the "phosphate ore". Fluorite has not been observed in the ore-body itself, but its introduction into the country-rock probably took place at an early stage during the phosphate mineralisation, the composition of the fluorite being nearer to that of the phosphate minerals than of the sulphides or oxides.

3. Xenoliths of altered granite-gneiss enclosed in the ore-body provided zones of weakness for subsequent

shearing, which resulted in the local brecciation and crushing of the ore. This movement probably gave rise to the unusual twinning and discolouration in some of the monazite crystals.

4. Siliceous solutions then permeated the ore-body and deposited magnetite and sulphides in the crush-zones interstitially to the phosphate minerals, and as disseminations in the wall-rock, where replacement of the earlier-formed minerals took place to varying degrees in each case. If gold is present in the ore, as indicated by some of the chemical analyses, then it would most likely have been introduced along with the primary sulphides. Towards the closing stages of this mineralisation, the solutions apparently became enriched in Cu^{++} and $S^{=}$, giving rise to the reaction series between magnetite and the sulphides. The quartz crystallised after "stoping out" sections and minerals of both the existing ore-body and the wall-rock.

5. Shearing at a later date gave rise firstly to brecciation and then recrystallisation of the quartz bodies, as shown by the linear attitude of the inclusions and the constituent quartz fragments respectively.

6. The formation of small quantities of siderite represented the final phase of the mineralisation.

7. Post-mineralisation faulting of the ore-body took place and is characterised by brecciation of the ore and the wall-rock along the fault-zones, and infilling by quartz. The unsheared quartz veins observed near the present ground surface may be of this age. Their shattering and subsequent infilling by secondary ferruginous material is probably related to tectonics of a much later period.

8. The age of the alteration of the magnetite to its respective secondary minerals, and of the copper sulphides to covellite, chalcocite, azurite, malachite and chrysocolla, cannot be established with certainty. Disregarding the relatively small amount of ferruginous matter which has been released by the alteration of chalcopyrite to covellite, the secondary iron minerals are more prominent and more widely distributed in the ore-body than their copper counterparts. This could possibly be attributed to selective oxidation in a zone of

secondary enrichment extending to well below the 300-foot level. Chrysocolla is restricted to near-surface levels and must have been formed by surface weathering; azurite and malachite were similarly formed but are more widely distributed. The resistance of the ore-body to weathering militates against the percolation through it of moisture; the effect of jointing, however, may have assisted the process, and the porous nature of the altered wall-rock would also have facilitated the passage of oxidising solutions.

(b) Age Determinations

Nicolaysen (1954) determined the ages of the first five minerals shown in Table No. 5, using lead-uranium, lead-lead and lead-thorium ratios. The determination of uranium and lead was done by isotope dilution and solvent extraction methods, and thorium was determined by isotope dilution and colourimetry. The age of the Sub Nigel monazite was established by Mendelssohn, Burger, Nicolaysen and de Villiers (1958) using stable isotope dilution methods and the same ratios. Nicolaysen's original figures for the micas from Jakhalswater and Kinderzitt have since been revised by Davis, Aldrich, Tilton, Weatherill and Jeffrey (1955-56, pp. 161-168) in the light of a more recently established half-life constant for rubidium-strontium decay, and are quoted in the table. The original figures obtained by Nicolaysen for the age of the Houtenbek monazite varied from 930 to 400 million years. The material on which the determination was done was suspect, however, and recent measurement of samples collected by Nicolaysen personally gave more agreeable results. Table No. 5, in which the mineral ages obtained by using different isotope ratios are compared, has been adapted from one published by Davis, Aldrich, Tilton, Weatherill and Jeffrey (1955-56).

The results of the age determinations on the Steenkampskraal monazite are disappointing in that they are not sufficiently diagnostic to be distinguished with certainty from the results obtained for South African pegmatite minerals. At first glance the Steenkampskraal mineralisation would seem to be somewhat older than the Namaqualand pegmatite mineralisation, but the possible margins of error in each case nearly overlap, so that the figures remain inconclusive. As it happens, there is adequate

Table No. 5.- Comparison of Mineral Ages (x 10^6 years) Obtained by Utilising Different Isotope Ratios

Locality	Mineral	Type of Occurrence	$\frac{A^{40}}{K^{40}}$	$\frac{Sr^{87}}{Rb^{87}}$	$\frac{Pb^{206}}{U^{238}}$	$\frac{Pb^{207}}{U^{235}}$	$\frac{Pb^{207}}{Pb^{206}}$	$\frac{Pb^{208}}{Th^{232}}$
Goodhouse, Namaqualand	Monazite	Pegmatite			930 ± 40	915 ± 50	880 ± 70	900 ± 30
Jakhalswater, Namaqualand	Muscovite	Pegmatite	970	960				
Kinderzitt, Warmbad, S.W.A.	Lepidolite	Pegmatite		985				
Steenkampskraal, Vanrhynsdorp	Monazite	Lode			1080 ± 60			990 ± 30
Houtenbek, Groblersdal	Monazite	Pegmatite			1950 ± 150 (average)			1950 ± 150 (average)
Sub Nigel Mine, Witwatersrand	Monazite	Vein?			2140 ± 40	2160 ± 40	2180 ±30	2010 ± 50

geological evidence on Uilklip to prove that the monazite mineralisation is distinctly younger than the emplacement of the pegmatites. It is unfortunate that these are the only determinations available for Namaqualand pegmatite minerals. With more information, Ahrens' method could be used to establish the convergent lead age for this mineralisation (1955, pp. 294-300). A figure thus obtained might well bear out the geological relationship between the monazite ore and the pegmatites.

On Roodewal there is also adequate geological evidence for relating the emplacement of the monazite ore to a pre-Nama age. The well-known Houtenbek monazite deposit (Anon., 1940, p. 289) is associated with Bushveld granite, and it is therefore interesting in the light of the accepted age relationships of the Nama and Transvaal Systems, that the work of Nicolaysen, de Villiers, Burger and Strelow (1958) should show the Houtenbek material to be approximately twice the age of that from Steenkampskraal. The figures obtained for the monazite are confirmed by the results of similar determinations on zircon and micas from the Bushveld Igneous Complex.

There is reasonably good agreement between the ages of the authigenic monazite from the Main Reef Leader in the Sub Nigel Mine. The average age of 2,150 ± 90 million years (Mendelssohn, Burger, Nicolaysen and de Villiers, 1958) is exceeded only by the age of 3,100 million years recorded by Liebenberg (1956, p. 162) for detrital monazite in the Dominion Reef System conglomerates. The margin of error for the Sub Nigel monazite overlaps with that for the Houtenbek pegmatite mineralisation, and on purely theoretical grounds the possible genetic association of these two monazites cannot be excluded.

Nicolaysen has unfortunately not commented on the age of the Steenkampskraal monazite, except to write that "It is possible that the primary Pb of the Steenkampskraal monazite ore-deposit is more radiogenic in character; in this case the calculated.......ages would be slightly lowered." The results of recent work on galena from the deposit have, however, corroborated the original corrections made for primary lead (personal communication).

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.
CeO_2				4.1	4.9	11.3	11.6	14.8	15.2	18.00	14.14	12.65	5.08	8.04	10.00	16.79	11.10
Rest of rare earth oxides	51.72	53.39	46.3	11.5	14.4	29.6	31.0	38.4	40.7	41.87	37.32	32.96	12.10	19.10	26.00	44.00	28.10
ThO_2	4.76	5.16	2.9	1.6	2.2	3.4	3.8	4.0	4.1	5.40	4.76	4.10	1.50	2.36	3.40	5.65	3.10
P_2O_5	24.44		26.9	9.5	11.8	19.8	17.3	18.3	21.5	11.86	19.64	18.79	8.40	11.09	14.66	22.47	14.66
SiO_2			4.1							6.15	15.42	15.50	24.10	30.90	28.58		31.10
Cu	5.59		2.0	0.9	1.0	1.6	1.3	2.2	0.0	0.99	1.03	7.70	0.92	1.13	0.54	1.3	1.40
Fe			1.9							5.21	5.04	8.12	10.30	7.73	4.67	5.69	3.64
S										3.62	2.83	3.35	3.23	1.29	1.49	4.02	1.51
MgO			0.5														
CaO			5.4									5.40	4.76	4.28	7.70		4.20
Al_2O_3												0.56					
Acid insolubles	4.80		4.3														
H_2O+			0.8														
Total	91.31		95.1							93.10	100.18	109.13	70.39	85.92	97.04	99.92	98.81
Au (dwts.)												0.10	0.18	0.42	0.45		

1. Assay done by The Standard Bank of South Africa, Limited.
2. do.
3. Assay done by the Industrial Consulting Laboratory for the Kava Import and Export Company. The difference between the total and 100% is made up of acid-soluble compounds of Al, Ti and Mn, and other elements in low concentration.
4. 100-foot level cross-cut intersection: upper 8" - west side[*].
5. do. upper 9" - east side.
6. do. middle 11.5" - west side.
7. do. middle 8" - east side.
8. do. lower 7.5" - west side.
9. do. lower 4" - east side.
10. Bore-hole No. 1 intersection.
11. Bore-hole No. 2 intersection.
12. Bore-hole No. 4 intersection.
13. Bore-hole No. 5 intersection: upper band 10.6".
14. do. lower band 1' 2.6".
15. Bore-hole No. 7 intersection.
16. Bore-hole No. 9 intersection.
17. Bore-hole No. 10 intersection.

[*] Assays 4 - 17 were done by the New Consolidated Goldfields Laboratory for the Anglo American Corporation of South Africa, Limited.

Table No. 7.- Comparison of Monazite Analyses

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
CaO	2.40	0.16	0.41	0.35		0.52	0.39	0.20	0.83	0.37	0.34
MgO	0.19			0.02		0.27			0.09	Tr	0.22
Ce_2O_3	17.70	30.38	27.37	22.63	31.85	21.08	31.63	31.90	22.00	32.29	31.41
$(La,Nd)_2O_3$	38.70	29.60	30.13	34.63	27.90	31.27	29.68	28.46	32.72	41.83	33.19
Y_2O_3	4.77*	1.33	2.14	4.66	2.93	3.53	2.86		1.15		5.08
Fe_2O_3	0.33	1.50	0.81	0.08	0.42	0.66	0.68	1.50	0.44	Tr	
Al_2O_3	1.14	0.10	0.17	0.10	0.21	0.80		0.17	1.20		
ThO_2	8.01	6.19	10.29	7.32	9.15	11.08	5.65	10.22	12.00		0.00
SiO_2	1.00	0.85	1.03	1.54		2.98	1.22	0.90	1.56	0.95	0.27
P_2O_5	26.10	29.70	27.67	27.89	27.45	27.52	26.81	26.82	27.22	24.90	29.29
U_3O_8	0.08			0.32					0.27		
PbO	0.05			0.33					0.53		
ZrO_2	0.01										
MnO	0.005								Tr		
BeO	0.01										
SnO_2	0.00						0.84				
C				Tr							
H_2O+	0.20			0.40		0.56		0.46	0.63		
Ign. loss		0.33	0.20		0.74		0.40				
Rem.						0.42					
Total	100.695	100.14	100.22	100.27	100.65	100.69	100.16	100.63	100.64	100.34	99.80

1. Steenkampskraal, Vanrhynsdorp Division, C.P., Union of South Africa.
   Analyst: Abraham Kruger, Division of Chemical Services, Dept. of Agriculture.
   *Quoted by analyst as $(Y,Er)_2O_3$.
2. Nsan Oban, Nigeria.
3. Ratnapura, India.
4. Dickens Township, Nipissing Dist., Ontario
5. Miandrarivo, Madagascar.
6. Ishikawa, Japan.
7. Impilaks, Finland.
8. Monazite sand, Travancore.
9. Gaya Dist., Bihar, India. H_2O includes H_2O+ 0.48, H_2O- 0.15.
10. Shinkolobwe, Katanga. Ce_2O_3 reported as CeO_2. Contains about 0.2% ThO_2.
11. Llallagua, Bolivia.

5. Composition of the Ore

(a) Chemical Composition

Of all the samples submitted for chemical analysis by different individuals, only one consisted of pure monazite; the rest were specimens of monazite ore as sampled at Steenkampskraal.

Analyses of the ore are presented in Table No. 6. They are unfortunately not complete, but give nevertheless the percentages of the main radicles constituting the minerals of economic importance. On the Assay Sheet of the ore-body (Map 6), the percentages of the total rare earth oxides (TREO), thorium oxide (ThO_2) and copper (Cu) from regular sampling on the 100-foot level, are presented graphically.

The analyses in both Table No. 6 and Map 6 show that there is:-

1. Great variation in the percentage of the respective radicles;
2. Appreciable variation in the ratio TREO:ThO_2, which, for a particular monazite occurrence, ought to be constant.

With regard to the accuracy of the assays, however, the following points should be borne in mind:-

(i) Chemical assays of the rare earth metals are very difficult to perform with a high degree of accuracy;

(ii) To achieve the required degree of accuracy in these particular assays, much experience is needed by the analyst;

(iii) at the time these assays were done, assays and especially analyses of rare earth minerals were something of a rarity in this country.

It is felt, therefore, that the results are not sufficiently accurate for comparisons to be made, and any attempt at recording variations in the TREO:ThO_2 ratio in the deposit would be unsuccessful as a result.

The analysis of pure monazite separated from the ore is given in Table No. 7, and compared with analyses of monazites from other parts of the world (Palache, Berman and Frondel, 1951, p. 694). The material used for this analysis was a flotation concentrate obtained from the Anglo American Corporation through the courtesy of Mr. V. Ward, who, together with Mr. Pinkney, was responsible for the metallurgical examination of the ore (Pinkney and Ward, 1958).

The concentrate was treated in turn with alcohol, a commercial detergent and very dilute hydrochloric acid in order to remove the flotation chemicals. After drying, the strongly magnetic fraction was removed by means of a hand magnet. Successive fractions of the remainder were then separated on a Franz Isodynamic Separator, each fraction being examined under the binocular microscope, and the process repeated until a pure monazite fraction was obtained. This fraction amounted to 33.7% of the original sample, the remainder being made up of sulphides, zircon, apatite, magnetite, and monazite impregnated by sulphide, magnetite or ferruginous material.

It is unfortunate that the analysis of the Steenkampskraal monazite does not permit the calculation of the atomic per cent of the individual rare earth metals. Murata, Rose and Carron (1953, pp. 292-300) have established the following semiquantitative rules for monazites from widely scattered localities, and it would be interesting to compare the figures for the Steenkampskraal monazite with these:-

(i) La + Nd is very nearly a constant at 42 $\pm$ 2 atomic per cent;

(ii) Pr is very nearly constant at 5 $\pm$ 1 atomic per cent;

(iii) Ce + Sm + Gd + Y is very nearly constant at 53 $\pm$ 3 atomic per cent.

(b) Radiometric Assays

The sampling of the outcrop of the ore-body for radiometric assay has already been described. The results, expressed in equivalent thorium oxide ($eThO_2$), are shown on the Assay Sheet (Map 6).

A factor derived from the TRLO:$eThO_2$ ratio can be used to compute the total rare earth oxide content of the ore, once it has been radiometrically assayed against a thorium standard sample. The calculation makes

Table No. 8.- Modal Analyses of Monazite Ore

Thin section no.	Monazite	Apatite	Magnetite, haematite, limonite, leucoxene	Total copper minerals	Pyrite	Zircon	Quartz	Total points counted	Limits of error in %	Remarks
A. SAMPLES FROM SURFACE										
16668	82.2	6.5	9.4			1.9		600	1.2-3.0	Ore, apparently high-grade, from western extremity of deposit.
16671	88.1	0.7	4.3	5.3		1.6		700	0.7-2.2	Average ore from "blow" in middle of deposit.
16672	83.2		8.3	6.7		0.8	1.0	600	0.3-3.0	Ore taken at depth of 7 feet in Brink's prospecting pit.
16674	87.0		11.1			1.9		600	1.0-2.7	Float; quartz veins in ore not taken into account.
16676	37.5	27.5	34.8			0.2		400	0.4-4.8	Ore with quartz veins (as for 16674) from western extremity.
18137	81.3	15.4	1.5			1.2	0.6	605	0.6-3.2	Ore enclosing xenoliths of altered wall-rock (disregarded).
B. SAMPLES FROM 100-FOOT LEVEL										
17947	48.6	34.4	5.2	7.8	3.1	0.9		346	1.1-5.3	Ore interlaminated with red feldspar from foot-wall contact.
17950	70.1	14.7		13.0	1.1	0.9	0.2	1000	0.3-2.9	Ore taken 190 feet west of cross-cut.
17951	80.6	7.2	5.2	5.7		1.3		403	1.2-4.1	Ore taken 100 feet west of cross-cut.
17952	80.1	1.3	7.7	2.5	6.8	1.6		597	0.8-3.2	Ore taken approximately 200 feet east of cross-cut.
18117	41.3	39.6	13.3	3.3	0.3	2.2		300	0.7-5.6	Foot-wall ore containing altered wall-rock, sulphides etc.
18140	72.3	6.1	16.0		4.0	1.6		800	0.8-3.2	Ferruginous ore taken 40 feet east of cross-cut.
18144	79.2	3.0	7.2	8.0		1.0	1.6	1200	0.6-2.3	Ore taken 100 feet east of cross-cut.
18145	75.9	3.0	7.2		12.3	1.6		1000	0.7-2.7	Ferruginous, sheared ore taken 120 feet east of cross-cut.
18146	54.3	32.3	5.8	6.3		1.3		1000	0.7-2.2	Stringers of ore in wall-rock from same locality as 18145.
18147	81.0	3.7	6.0	6.0	2.0	1.3		600	0.8-3.2	Very granular ore taken 170 feet east of cross-cut.
18154	51.8	19.7	20.5	3.5	2.5	1.3		300	1.3-5.6	Stringers of ore occurring with primary sulphides in altered wall-rock 170 feet west of cross-cut.
18155	84.6	4.3	9.8			2.0		400	1.3-5.0	Ferruginous ore enclosing altered wall-rock from same locality as 18154.
18156	55.9	8.5	3.3	8.1	21.7	0.3	2.2	900	0.4-3.4	Sheared ore replaced by sulphides 190 feet west of cross-cut.
18157	78.8	7.8	7.0	3.0	1.7	1.7		700	0.8-3.1	Sheared ore containing altered wall-rock 200 feet west of cross-cut.
	68.179.	13.257.	114.2	67.6.						
C. SAMPLES FROM DIAMOND-DRILL INTERSECTIONS										
18503/A882	76.9	3.4	5.0	5.5	8.3	0.6	0.3	800	0.4-3.0	Compact ore containing interstitial sulphides and oxides.
18504/A882	82.4	3.1	0.7	9.0	4.5	0.3		700	0.4-3.0	Ditto, slightly ferruginous.
18505/A883	47.0	36.4	10.8	3.2	2.4	0.2		500	0.4-4.6	Contact between ore and quartz-rich granite-gneiss.
18506/A884	60.8	29.3	4.2	4.8	0.4	0.5		600	0.5-4.0	Ferruginous ore at contact.
18509/A884	81.5	0.2	3.8	1.0	12.7	0.8		600	0.4-3.2	Highly concentrated monazite ore enclosing wall-rock.
18510/A885	42.5	47.4	6.3	2.2	1.4	0.2		410	0.4-5.1	Ore rich in apatite, containing xenoliths of wall-rock.

use of the results of the chemical analysis (see Table No. 7) as follows:-

$$\frac{\text{TREO}}{\text{eThO}_2} = \frac{61.17}{8.25^*}$$

$$= 7.41$$

1.137

(c) Volumetric Composition

Modal analyses of representative ore-samples are given in Table No. 8. A Glagolev point-counter as described by Chayes (1949, pp. 1-11) was used. The proportions of the respective minerals have been reduced to per cent; the total number of points counted in each case is shown in one column, and the limits of error according to the curves of Barringer (1953, p. 33) are indicated in another column.

Pronounced replacement of the ore by quartz, and the presence of wall-rock gangue, have been disregarded. To simplify the interpretation of the results, all the iron minerals except pyrite were included in one group, and all the copper minerals in another.

The following features emerge from the counts:-

1. Except where the proportion of oxides and/or sulphides is very high i.e. where extensive replacement of the phosphate minerals has taken place, the total phosphate percentage (monazite + apatite) is in the vicinity of 80%+, irrespective of their individual percentages;
2. The proportion of apatite tends to increase in depth;
3. The proportion of zircon tends to decrease in depth;
4. The oxide and sulphide minerals occur independently of the proportions of the phosphate minerals.

---

* Radiometric assay of monazite involves the measurement of radiation from the uranium as well as the thorium component of the sample; the apparent $\%\text{ThO}_2$ for this monazite, as revealed by radiometric assay, is therefore expressed as

$$\%\text{eThO}_2 = \%\text{ThO}_2 + (3 \times \%\text{U}_3\text{O}_8)$$

$$= 8.25$$

The results of the chemical analyses, radiometric assays and modal analyses, whether for systematic or random sampling, indicate irregular proportions of the individual minerals throughout the deposit. Attempts to draw variation curves from the results have been unsuccessful. Unfortunately chemical, modal and radiometric analyses were not made of the same samples; those that are available can therefore not be compared inter se.

Taking the "phosphate ore", unreplaced by oxides and sulphides, as a unit, however, the total phosphate minerals maintain a fairly steady proportion, in spite of the fact that the percentages of apatite and zircon increase and decrease with depth, respectively. If the zircon content, in the light of its small variation, can be regarded as constant, as well as the combined proportions of monazite and apatite, then the figures support the petrographical evidence that monazite, apatite and zircon represent a common period of mineralisation. The figures also bear out the fact that the oxide and sulphide mineralisation has taken place quite independently of the prior phosphate mineralisation, and has been capable of upsetting the total phosphate mineral proportion by replacement of these minerals.

G. Mining, Ore-dressing and Production

The mining of the ore-body, being a lode with well-defined boundaries and few major irregularities in dip, is in theory a simple matter, and the skeleton layout of the mine sketched in Fig. 7 ought to be quite straightforward.

On top of the koppie at the surface, near the original prospecting pit, a vertical shaft was made 100 feet deep, and a cross-cut was made from it southwards at that depth to intersect the ore-body. From the intersection, drives were developed along strike to east and west, thereby forming the 100-foot level.

Approximately opposite the 100-foot cross-cut, a winze was made on the dip of the ore-body to the 300-foot level, and another main level was developed east and west of it at 200 feet.

The picture is then complicated by development along sub-levels with raises and other winzes between them for the purpose of following the lode and its small apophyses to the best advantage, and to overcome displacement due to faulting.

Hoists operate at both shafts. The ore is stoped out by the room-and-pillar method and falls into the main levels or sub-levels. The ore between the surface and the 100-foot level is lifted from the vertical shaft, and ore below the 100-foot level is lifted from the 300-foot level by means of the inclined shaft. The ore from the vertical shaft is transported to a chute constructed over the mouth of the inclined shaft, so that the hoist which operates there can feed ore from both sources into the ore-dressing plant.

After exhaustive tests and experiments on bulk samples of the ore had been conducted by the Anglo American Corporation, a flow-sheet for a concentration plant was drawn up. As far as is known, there was at that time no plant treating ore of this nature, from which information could be obtained. In view of the complexity of the concentration process, the lack of power, transport facilities and water for either mining or domestic use, a great deal of thought had to be given to the design of the final plant (MacConochie, 1957, pp. 95-100). The finely divided and often disseminated nature of the monazite requires the ore to be finely ground. The application of standard gravity separation methods was found to be uneconomic because of the high tailing losses involved in the treatment of such fine material, and flotation is therefore employed to concentrate the monazite instead.

Briefly, the ore is crushed and the pulp from classifiers is treated by flotation in two stages. The first removes iron and copper sulphides, and the second floats off the monazite. The concentrate is filtered, dried and bagged for export. The plant is capable of producing a steady concentrate containing roughly 50% total rare earth oxides under normal conditions. If the amount of gangue entering the plant is reduced by hand-picking or by recently introduced heavy medium techniques, the efficiency is increased. The fineness of the secondary minerals from the altered wall-rocks tends to hamper the flotation process, as they form a very fine slime suspension, and for this reason water can pass through the plant once only. The details of the beneficiation process and its development are set out by Pinkney and Ward (1958).

The consumption of water by the plant reaches tens of thousands of gallons per day. It is transported a distance of 65 miles from the Olifants River at Klawer by South African Railways water-lorries, which convey the concentrates to the station on the return trip.

Production started in November, 1951, and 41,817 tons of monazite concentrate had been produced by the end of 1957. The production of 9,314.21 tons of concentrate during 1957 rendered South Africa the major world producer of thorium and rare-earths (Kremers, 1958, p. 145; Paone, 1958, p. 144).

IV.- The Monazite Deposits on Roodewal and Uilklip

A. History

The deposit on Roodewal forms a slight but conspicuous feature at the surface of the ground. It had been known by the local inhabitants for a long time, but had been regarded as a type of fulgurite and therefore of no economic significance. With the interest aroused by the prospecting of the Steenkampskraal deposit, and the subsequent identification of monazite in the ore, however, it was not long before the similarity between the two deposits was recognized. The Roodewal deposit was "rediscovered" by a jackal hunter in 1952. Prospecting subsequently in the immediate vicinity of this deposit, Mr. C.A. Gibson of the Anglo American Corporation traced further small deposits on Uilklip from the radiation afforded by their float patterns.

B. Location

The deposits are situated on either side of, and very near to, the boundary line between Roodewal and Uilklip, in the south-western and south-eastern corners of the farms respectively. They are approximatelt two miles by farm track from the secondary road between Kliprand and Vanrhynsdorp. As the crow flies they are seven miles NNE. from the Steenkampskraal deposit, and a total of 61 miles by road from Vanrhynsdorp (see Maps 1, 2, 3 and 8).

Sediments of the Kuibis Series have been eroded away, exposing the crystalline basement in a small, northward trending river-valley. Wherever the sediments remain they form krantzes or steep scarps, and the level of the exposed granite-gneiss drops from them towards the bed of the stream. The deposits occur on either side of the small valley so formed. Scree from the krantzes and locally derived detritus from the crystalline basement build parts of the valley slopes, and the deposits were originally obscured to a great extent by these accumulations.

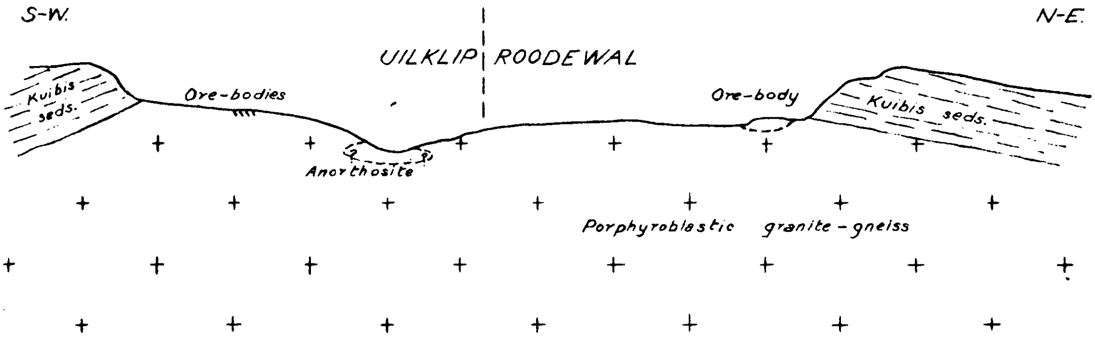


Fig. 18.- Diagrammatic section through the mineralised area on Roodewal and Uilklip.

C. Geology of the Deposits

1. Roodewal

The deposit occurs in porphyroblastic granite-gneiss at the foot of a small krantz of Kuibis sediments, and before prospecting operations began it was largely covered by these sediments and scree. As originally exposed, the deposit formed a "reef" or "blow" which, at its most prominent point, stood about 5 feet above the surface of the ground. It had a maximum width of 16 feet and a length of outcrop of about 90 feet. Having weathered to a dark-brown colour and being stained here and there by malachite and chrysocolla, and surrounded by a considerable quantity of float, it provided a local feature which stood out markedly from the more easily eroded granite-gneiss.

The strike of the ore-body as exposed was from north-east to south-west, but the contacts were too poorly exposed originally for the dip to be observed. The deposit appeared to be horizontally bedded and to rest on the granite-gneiss. The contact apparently dipped gently northwards. There were distinct, near-vertical shear-planes both in the ore and in the country-rock.

Prospecting by the Anglo American Corporation has presented a very much clearer picture. Map 8 shows the area cleared of rubble and scree, and the actual behaviour of the ore-body. The greatest development of the deposit, at its southern extremity, is in a shear-zone in the granite-gneiss. This shear-zone trends parallel to the foliation but dips more steeply to the south-east. The ore-body, however, swings out of the shear-zone northwards some 75 feet from its south-western extremity, then symmetrically east and north again. It becomes narrower along strike until it is a mere 3 or 4 inches thick at its northern extremity.

Here the ore-body is truncated by the pre-Nama erosion surface, and is overlain by boulders of granite-gneiss which are separated by fissure-fillings of arkosic material. The boulders have different directions of lineation. The fissure-fillings in contact with the ore are very weathered, and consist of limonitic and siliceous, calcareous tufa passing upwards into sandy, feldspathic sandstone. These fillings, which are of Nama age, contain small quantities of monazite some distance from the contact.

Prospecting trenches that have been sunk across the strike of the deposit reveal its structure and relationship to the country-rock. At its south-eastern extremity, the ore-body abruptly decreases in thickness from 18 feet to a number of thin, parallel stringers which pinch out in the granite-gneiss. At its greatest development in the south-west trending limb, the ore-body and stringers dip steeply north-west on the north-west contact, and steeply south-east on the south-east contact, giving the impression that there is an increase of thickness in depth. These features are deceptive, however, and diamond-drilling by the Anglo American Corporation has shown the ore-body to pinch out at very shallow depth indeed. As the body swings to the north, the dip is to the east and slightly shallower, becoming more so along the strike, and then it steepens again on the northernmost limb. In general, therefore, the lode may be described as trending north-east with a predominant dip to the south-east.

The ore-body and the surrounding granite-gneiss have undergone jointing and slight movement along faults. This has produced slickensides along planes in the ore.

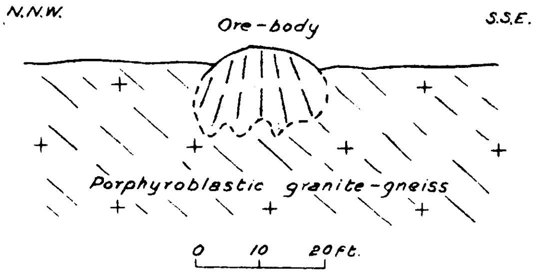


Fig. 19.- Diagrammatic section across the monazite deposit on Roodewal.

The faults are probably old joint-planes along which post-Nama movement has taken place. The joints in the granite-gneiss are too irregular to be regarded as primary in origin, and are considered, therefore, to be related to the post-Nama tectonics. Their surfaces are smooth, coated with limonite and sometimes slickensides as well.

Rapid changes in the strike of the ore-body could be misinterpreted as having resulted from faulting, especially where they are accompanied by abrupt changes in thickness. Post-Nama jointing and faulting have affected the ore-body to a small degree as described. In one place it has been eroded away together with the wall-rock, and the resultant depression has been filled by boulders of granite-gneiss and arkosic matter. The whole is now consolidated and obscures a good deal of the ore-body. The apparent change in thickness and the sudden transition from granite-gneiss to monazite ore could be erroneously dismissed as having resulted from faulting. There is, besides, no fault-breccia or filling to indicate a lateral movement of at least 10 feet, or the vertical throw which would have been required to thin the lode from a width of about 15 feet to an apparent width of 1 or 2 feet.

The granite-gneiss in which the ore has been emplaced is typical porphyroblastic granite-gneiss. Its foliation strikes east-west and dips south, and an east-west lineation is brought out by recrystallised quartz. The granite-gneiss is a deep-red colour over parts of the southern half of the area (Map 8), and this is considered to be due to hydrothermal alteration and to be associated with small, frequently occurring zones of shearing. In the south-eastern corner of Uilklip, small, en echelon quartz veins are present in the granite-gneiss parallel to the foliation, and a large quartz vein which is transgressive to the foliation occurs south-west of them.

Mineralisation has taken place on the site of shearing in the granite-gneiss, but has not been controlled by it. Rather, the minerals tend to be associated with zones of hydrothermal alteration in the granite-gneiss, and so this alteration seems to be a prerequisite to the mineralisation. The altered rock varies in colour from white to green due to the presence of one or more of sericite, epidote and chlorite. Where stained by secondary iron oxides, the product is dark-red in colour. The wide-spread dissemination of the phosphate minerals in the wall-rock, apart from their presence in the main ore-body and stringers, suggests that thorough impregnation by mineralised vapours or solutions followed the hydrothermal alteration.

A lode of titaniferous magnetite, largely altered to haematite and leucoxene, cuts the foliation of the granite-gneiss in the second trench, at right angles to the strike of the ore-body, illustrating the irregularity of replacement. Near the point where the ore-body is partially eroded and covered by boulders and arkosic material, more haematite is present in small, irregular veins and stringers. It exhibits good crystal form pseudomorphous after magnetite. In polished section, the leucoxene may be observed along the octahedral exsolution-planes (polished section D.P. 169). The haematite is usually characteristic of the contact between the monazite ore and the granite-gneiss.

2. Uilklip

The ore is present in the form of pods, small veins or lodes, and stringers, all of which are rather irregular both vertically and laterally. A predominantly east-west strike can, however, be recognised, and most of the ore-bodies dip in a northerly direction. Their size varies from that of mere mineral grains disseminated over a few inches, to bodies a few feet in length and girth. The maximum thickness measured was 2 feet. It is assumed that the greater part of the ore has been removed by erosion, since a great deal of material has been found as float and in Recent conglomerate in the stream-bed.

The country-rock is porphyroblastic granite-gneiss, generally biotite-rich, and usually weathered. In the stream-bed, a small patch of anorthosite is exposed. It grades outwards into the granite-gneiss through zones of white, then pink, feldspar-chlorite rocks containing a zone of recrystallised quartz, and deep-red granite containing much epidote. A faint horizontal foliation is provided in the anorthosite by the orientation of the flakes of biotite.

Veins of pegmatite cut the foliation and lineation of the granite-gneiss. They vary from fractions of an inch to a few feet in thickness, and up to 200 feet in length. Their presence provides a valuable clue for dating the mineralisation. In the northern lot of exposures, the largest ore-body cuts two parallel pegmatites, and two small ore-bodies stop against two more parallel pegmatites. This indicates quite clearly that the mineralisation is post-pegmatite in age.

A structural map (Map 9) of the crystalline basement, drawn by tentatively joining the strike-lines of the foliation, shows a distinct "whorl" of the type described from Steenkampskraal. It seems significant that mineralisation has again taken place where the strike of the foliation changes markedly from the regional pattern, and it might suggest that mineralisation had favoured a weakness in the crust at this point. The lineation in the granite-gneiss maintains a very constant east-west trend in spite of any change in the direction or the dip of the foliation.

The monazite ore can be traced by following the small zones of alteration in the granite-gneiss. The wall-rock is characterised by sericitisation of the feldspar, and the presence of abundant chlorite and secondary ferruginous matter. The foot-wall contacts are generally sharp, but the hanging-wall contacts, especially if nearly parallel to the foliation of the granite-gneiss, are more highly altered and irregularly mineralised. The whole of the country-rock is well jointed, and the joints pass through the pods of ore. These joints are not mineralised, which indicates that they are of a later age. Post-mineralisation faults displace the ore-bodies slightly and occasionally truncate them altogether. The fault-planes are filled by mylonitic material containing abundant chlorite, hydroxides

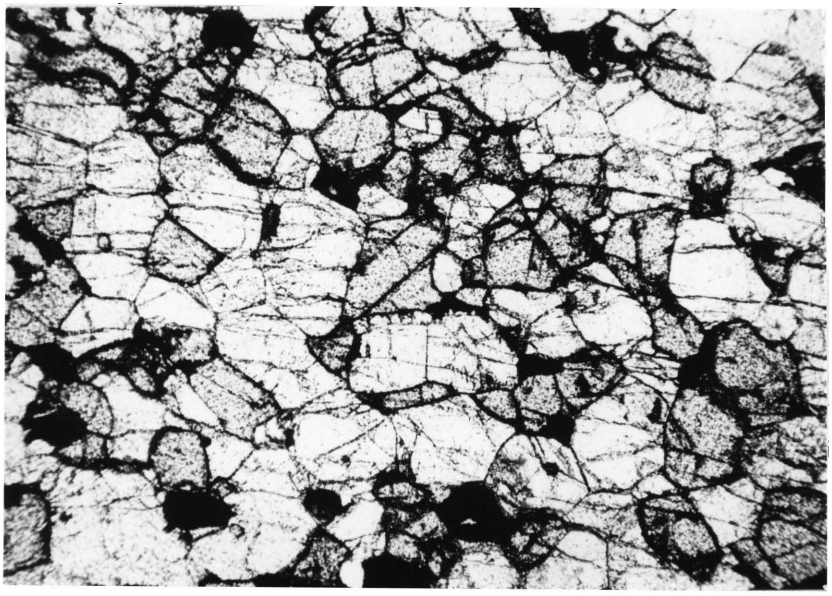


Plate XLVII.- Parallel fractures due to shearing in apatite-rich ore. Plane polarised light. x 32. 18152, Roodewal.

and other secondary minerals.

A common feature of the pods is their near-horizontal disposition to one another, at slightly different levels in the granite-gneiss. It would seem as if the mineralising solutions or vapours had "soaked" the granite-gneiss along flat-lying joints, or in the case of ore with better defined boundaries, along more steeply dipping joints, and so gave rise to this feature.

D. Mineralogy of the Deposits.

The macroscopic similarity of the ore to that of Steenkampskraal is borne out by petrographical examination (18512-18515). There are, in fact, no essential differences, and the relationships of the minerals to each other and to the altered wall-rock are exactly the same.

In a thin section cut from a sample of the Roodewal deposit (18512), part of the wall-rock contains a few grains of highly altered amphibole, which can be recognized by its cleavage. The occasional occurrence of hornblende in the granite-gneiss is mentioned by Brink (1950, p. 163).

The mosaic texture of the equigranular "phosphate ore" is very striking (see Plate XLVII). The ore encloses many xenoliths of altered wall-rock, and its replacement of the wall-rock is very distinct. In the thin sections cut from samples of the Roodewal ore, parallel fractures pass through all the mineral grains regardless of their orientation or cleavage (Plate XLVII). These fractures run in the same direction as the vertical shear-planes in the ore-body and are no doubt related to them. This shearing must, therefore, post-date the mineralisation; even the replacement of the ore by quartz, which is the youngest mineral, is not controlled by it. It probably represents renewed movement along the original shear-plane in which the mineralisation took place.

The monazite is well cleaved, but seldom twinned, and shows no discolouration of the sort recorded on Steenkampskraal. Monazite and apatite occur for the most part in normal proportions, but may tend locally to exclude one another as well (Plate XLVII).

Aluminian strengite (barrandite) is present in small quantities interstitial to the monazite crystals on Roodewal. It is present in fine blades, flakes, laths and spherulites, and in "concertina" or radiating aggregates (18513). The strengite is light-buff to brownish in colour, and is nonpleochroic; the darker tints are apparently due to alteration. The basal sections are euhedral and pseudohexagonal in outline. The optical character ($2V_\alpha = 74°$), positive elongation and maximum extinction angle $\gamma.cl = 6°$, were established on the Universal Microscope Stage. There is one good cleavage parallel to the basal pinacoid, and another distinct cleavage at right angles to it. The mean index of refraction is 1.68; the birefringence is low. In a twinned crystal, the composition-plane is parallel to the basal pinacoid, and there is a maximum symmetrical extinction angle of 6°. The mineral was identified by means of X-ray powder photographs which placed it in the scorodite-variscite group, and microchemical tests for Fe^{+++} and $PO_4^{\equiv}$ were positive. Qualitative spectrographical analysis of a very small sample confirmed the presence of Fe and Al (probably Fe > Al) and the absence of As. The mineral dissolves in 1:1 HNO_3 with difficulty.

Jarosite forms finely crystalline, granular aggregates interstitial to the monazite in the same thin section. It is weakly pleochroic in shades of yellow. The birefringence is extreme, and approximate determinations of the refractive indices gave $\omega = 1.81$ and $\varepsilon = 1.72$. The jarosite gave a distinctive X-ray powder pattern, and the identification was confirmed by positive microchemical tests for Fe^{+++}, K^+ and $SO_4^{=}$. This mineral is also present in very small quantities.

Zircon is more abundant than at Steenkampskraal, and forms 4% of the ore where it is best developed. The grains are euhedral, oval or round in shape, and are usually strongly zoned.

The sulphides are represented by pyrite, chalcopyrite, galena, covellite and chalcocite. The galena is more plentiful than at Steenkampskraal. Alteration of the copper minerals at the ground-surface has yielded malachite and chrysocolla.

Very little magnetite remains, having largely been altered to haematite and limonite. The successive stages of the alteration are quite distinct. Abundant leucoxene occurs along octahedral exsolution-planes in the altered material (polished section D.P. 169). Very little free haematite remains in the ore-body; most of it is preserved as impregnations in monazite, and the rest has been altered to limonite.

Quartz occurs in somewhat irregular blebs, replacing the ore-minerals in the same way as in the Steenkampskraal deposit. It exhibits no strain shadows or signs of recrystallisation.

E. Prospecting Methods

The prospecting in this area was done in the first instance by the Anglo American Corporation. The outcrop on Roodewal was the only one known at the start, and it was through systematic traversing of the rest of the area with a portable Geiger-Müller counter by Mr. C.A. Gibson, the geologist in charge, that the other deposits were located on Uilklip. Traverses were made across the slope of the ground to establish a float pattern, and having been found, the float was then traced back to its origin.

By far the greater part of the deposits was covered by detritus and scree, and the area had to be cleared as shown on Map 8 before information could be gathered. Trenches were made across the deposit on Roodewal, and the middle and southern exposures on Uilklip. In addition, diamond-drilling was done on Roodewal to trace any extension of the ore-body in depth. The results were very disappointing, however, and showed the ore to be restricted virtually to what had already been exposed near the surface of the ground.

At about the time this prospecting came to an end, the author and Messrs. P.W. de Lange and Z. de Velde Harsenhorst of the National Physical Research Laboratory, were assessing the capabilities of car-mounted radioactivity detection equipment for field use. The relatively undisturbed nature of these deposits presented a unique opportunity to test the C.A.R.G.O.* unit. Traverses were made across the slopes from the deposits on either side of the valley, in order to determine the sensitivity of the equipment to naturally distributed float. It was also hoped to establish the measure of success which might be expected from traverses done in the ordinary course of a survey for radioactive deposits.

Detailed descriptions of the C.A.R.G.O.

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* C.A.R.G.O. is a mnemonic derived from car-mounted Geiger operation.

equipment and its use have already been published by Simpson (1954, pp. 57-60) and Bowie, Hale, Ostle and Beer (1955, pp. 1-23). Briefly, it consists of a ratemeter-type of Geiger-Müller counter and a scintillometer, both connected to automatic recording equipment, and mounted in a short wheel-base Land Rover. When the instruments are operating, a continuous record is made. This is in the form of a graph of the radioactivity registered in counts per minute, vs. the time or distance travelled by the Land Rover. The use of both instruments simultaneously, apart from providing records of different sensitivity, also provides a check in accuracy of one against the other. As it happened, the scintillometer was at fault for some of these particular traverses, and so the results from the ratemeter records were used to compile the isorad map of the area (Map 10).

The results indicate quite clearly how the float from even such small deposits becomes distributed, and can be detected by the increased radiation it affords above the background count. Especially significant is the fact that the float does not necessarily become concentrated in the stream-bed, but is more evenly spread over the sloping ground. The minerals from the deposit have a high specific gravity, and those that do reach the stream-bed make their way to the bottom of the detritus and are easily covered by lighter sand and silt. These sediments effectively mask the radiation, and prevent the minerals from being detected.

V.- Detrital Deposits in the Nama System

The relationship between the radioactive mineral deposits and the Nama System could not be established with certainty until the disconformable contact between the lode and the overlying Nama sediments was encountered on Roodewal. The fact that the ore-body is truncated by the pre-Nama erosion surface, and the presence of monazite in the overlying arkose, indicate immediately that the basal formations of the Nama System could conceivably carry detrital concentrations of monazite, which had undergone mechanical weathering and been removed by erosion from the primary deposits in the Archaean Complex.

How far the monazite would have been transported was a matter of conjecture: the exposed basal sediments of the Kuibis Series were examined, however, for a radius of approximately one mile around the Roodewal-Uilklip occurrences, and a banded sandstone which was radioactive over a small area was discovered. It occurs on Uilklip, immediately underlying Schwarzkalk limestone on the down-thrown side of a small dip-fault in the south-eastern portion of the farm (see Maps 2 and 3). This is much higher in the succession, therefore, than might be expected. The bands are thin, alternating layers of ferruginous and non-ferruginous sandstone; a superpanner concentrate of the heavy minerals contains detrital grains of monazite and zircon.

Following upon this discovery, Mr. de Velde Harsenhorst, during the course of traversing with the C.A.R.G.O. unit on Leeuw Kuil, located three radioactive areas at the contact between the Kuibis Series and the Archaean Complex. This farm is adjacent to the area that had already been mapped, so the mapping was extended to include it as well, and the deposits were examined at the same time.

' They occur in a radius of one and a half to two miles from the nearest known primary deposit, that on Roodewal (see Maps 2 and 3). The radioactive zones were traced with the portable probe unit of the C.A.R.G.O. scintillometer, and were found to be intercalated in the basal portions of the feldspathic sandstone and arkose, very near to the contact. They are flat-lying, thin and lenticular. The material is coarse-grained and dark in colour, being stained by secondary iron minerals. The occurrences are small in size, the most extensive one (the southernmost) having been traced for approximately 400 feet along strike. The dark-coloured layers of the rock contain the radioactive minerals, as they do on Uilklip; heavy mineral fractions separated from these layers contain monazite, highly impregnated and coated by ferruginous matter, zircon, and highly altered titaniferous magnetite. All the grains are well rounded. Although the layers occur over a thickness of 6 feet of strata, they are very narrow by comparison, seldom exceeding 2 inches in thickness, and it is doubtful whether they can ever be anything other than of academic interest. The most radioactive of the random samples that were taken, assayed 0.3% (6 lbs./ton) $eThO_2$.

VI.- Other Occurrences of Radioactive Minerals in the Area

During the course of field-work in the area, many and varied reports were received of suspected occurrences of radioactive minerals. All except two of them turned out to be groundless.

One of these occurrences is on the farm Taaiboschoek, Calvinia Division, where the Archaean Complex has been exposed through erosion of the Dwyka Series. Numerous pegmatites occur there, and one of them, near the Trigonometrical beacon Heuningnes 9 in the north-eastern corner of the farm, contains slightly radioactive columbite-tantalite. This is, to the best of the author's knowledge, the southernmost pegmatite mineralisation of its kind, and may indicate the position of the southern, mineralised, marginal zone of the Archaean Complex in the western Cape Province, corresponding to the northern, mineralised pegmatite zone along the Orange River. The locality is marked on field-sheet 8 in Fig. 1 and on Map 1.

The other occurrence is on the farm Meul, 20 miles NNW. of Bitterfontein on the main road to Garies. Diamond-bearing gravels cover an irregular erosion surface which now forms the northern slopes of the valley of the Swart Doring River. The clayey matrix in which the water-worn pebbles are set contains distinct quantities of "black sand", which was found in the field to be slightly radioactive. When this is washed and concentrated, a virtually magnetite-free, ilmenite sand is obtained, which contains a few per cent each of monazite and zircon. The locality is marked on field-sheet 10 in Fig. 1 and on Map 1.

Traversing with a portable Geiger-Müller counter across the strike of the granite-gneiss and metasediments resulted in the discovery of slightly radioactive quartz veins on Karragas, portion of the farm Kobeeb, Vanrhynsdorp Division. The locality is indicated on field-sheet 5 in Fig. 1 and on Map 1. The veins are en echelon in distribution and outcrop intermittently over a distance of 600 feet, the largest occurrence being about 50 feet in length and a maximum of 2 feet in width. They are interfoliated with the metasediments and have apparently recrystallised to accommodate the tectonics which gave rise to them. The quartz bodies and an adjacent biotite schist are ferruginous, and are enriched in patches by disseminated monazite and xenotime, which were identified in a heavy mineral concentrate separated from the crushed rocks. The occurrence is of no economic importance, but does indicate that radioactive mineralisation post-dating the formation of the Archaean Complex has taken place in this part of the area as well.

Traversing of the whole area by Mr. de Velde Harsenhorst with the C.A.R.G.O. unit followed the author's mapping of the geology and topocadastral features by plane table. No radioactive deposits other than those already described were discovered, but a few points of interest did emerge which could be mentioned at this stage.

Of all the crystalline rocks traversed in the area, the porphyroblastic granite-gneiss provides the highest radiometric normal. Unusually high radioactivity is encountered locally in the granite-gneiss on Leeuw Kuil and Warm Viool (approximately in the centre of field-sheet 14 in Fig. 1 and on Map 1). The granite-gneiss in the former locality is dark in colour and apparently somewhat altered; a heavy mineral concentrate separated from the crushed rock contains abundant zircon, to which the abnormal radioactivity may be ascribed. The granite-gneiss from the latter farm, by contrast, appears to be normal, but a heavy mineral fraction similarly concentrated from it contains abundant zircon, and also monazite. Its radioactivity could therefore be ascribed to both minerals.

Naturally concentrated "black sands" in the flatter parts of the area are often responsible for high radioactivity. This is due to the presence of abundant zircon and monazite.

The generalised basement structure map of the Roodewal-Uilklip deposits (Map 9) shows a small "whorl" in the strike of the foliation near the Kruispad - Leeuw Kuil boundary. Unfortunately, exposures of the granite-gneiss here are poor, and the structure is by no means definite. It seems significant, however, that the radioactivity from this section of the granite-gneiss is very much higher than that obtained by traverses over the same rock-type elsewhere in the immediate vicinity. Although no sign of monazite mineralisation was observed during mapping, the radioactivity anomaly that is repeatedly encountered here indicates that some mineralisation has definitely taken place.

VII.- Minerals of Economic Importance other than Monazite

The only minerals which occur in economic quantities in the area are those found in the monazite deposits. These have already been described.

Excavations for plant foundations and pipe-lines on Steenkampskraal exposed several zones of hydrothermal alteration, slightly mineralised by malachite, galena and fluorite. Fluorite also occurs in a hydrothermal zone near the monazite deposit on Roodewal, and as these appear to be small replacement deposits in the granite-gneiss, they are possibly related to the monazite mineralisation.

Small veins of barite are present in a shear-zone near the homestead on Uilklip (see Maps 2 and 3). They outcrop intermittently over a distance of 400 to 500 feet and reach a maximum thickness of 4 inches.

Reference has already been made to small occurrences of magnetite at the contacts between granite-gneiss and metaquartzite (see p. 17; Maps 2 and 3).

In the Nama System, disseminated cubes of limonite pseudomorphous after pyrite form replacements in the lower members of the Kuibis Series, and in the grit and arkose of the Schwarzkalk Series. The pseudomorphs are largely euhedral, up to 2 inches in diameter, and the striations which are typical of pyrite, are retained both on themselves and on their casts (see Plate XVIII). The individuals are perfectly discrete and no mineralising veins or stringers were observed between them. Large crystals occur near the base of the succession, and small ones further away from it. In diamond-drill cores, pyrite is present in quartzite and grit , and calcite, pyrite and chalcopyrite fill joints in shale.

Deposits of gypsum were found on the farms Kalk Gat Vlakte and Zoovoorby, to the east of the area covered by Map 2. They are situated at intervals in river banks, extending in each case for approximately 2 miles. No sampling could be done or a detailed survey made at the time of discovery. The mineral occurs beneath a capping of surface limestone which is everywhere present in the immediate area. Crystalline gypsum is well developed in the usual fawn-coloured gypsiferous earth. It might have originated from the overlying surface limestone, but the fact that it often gives rise to the latter by weathering, suggests that it has originated from the Schwarzkalk Series which outcrops near by. In this Series, sulphides for oxidation, and lime, are both available to form gypsum. Wasserstein (1935, p. 33) proposes a similar origin for other gypsum deposits near Vanrhynsdorp, where the Malmesbury Formation appears to have supplied the material to form the gypsum. The gypsum beneath the surface limestone in the area described by the present author is therefore probably more extensive than that which is exposed.

VIII.- Underground Water

In this semi-arid area, with its irregular and uncertain rainfall, underground water is very valuable and has been difficult to locate. Successful bore-holes have been drilled in dipping and folded Nama strata, in granite-gneiss overlain by Recent deposits, and in river-banks for seepage water. Unsuccessful holes have been drilled without adequate regard to structure and topography, or at random in river-banks in hopes of finding seepage water. The strength of the supplies is not known, but is probably well under 1,000 gallons per hour in each case. The quality of the water varies from slightly to strongly brackish.

Natural springs occur to the north of the area covered by Map 2 on the farms Brakfontein, Remainder of Tafelberg Lot B, and on Puts, where slightly to very brackish water issues from fracture-zones in the metasediments. Except for water which is very brackish, it is suitable for domestic use and for stock.

Apart from the shallow wells that have been sunk to exploit these springs, no bore-holes or wells have been sited on shear-zones or faults in the area, most of which are regarded as promising for underground water.

IX.- Discussion

A. Possible Sources of the Radioactive Elements

The geochemical affinity of primary thorium-bearing minerals for carbonatitic, alkaline and granitic igneous rocks, and particularly their residual solutions, is well established. These minerals find prominence in the pegmatites and hydrothermal veins associated with these rock-types (Frondel, 1956, p. 576; Kerr, 1956, pp. 36-37).

The epigenetic nature of the mineralisation having been established, it might logically be related to Jansen's third phase of intrusive activity in the Archaean Complex, which is represented west of Bitterfontein by the following sequence of rock-types (1955: 1956, pp. 6-8):-

1. Dykes of lamprophyres (minette, kersantite, camptonite), gabbro and pyroxene diabase;
2. Intrusive bodies composed of syenodiorite, syenite, quartz syenite and granite, and small intrusions of aegerite syenite;
3. Dykes of bostonitic rocks (bostonite, bostonite porphyry, quartz bostonite), syenite aplite, gauteite and sölvsbergite;
4. Large dykes of quartz porphyry, alkali granite porphyry and occasionally granophyre;
5. Large intrusions of granite.

Jansen considers that the origin of these younger rocks could possibly be found in a mobile palingene magma which originated by large-scale anatexis of the porphyritic rocks and also of the gneissic and metamorphic rocks. The sequence of emplacement is characterised by a gradual increase in the $K_2O:Na_2O$ ratio, the ratio for the granites being approximately equal to the ratio for the Pink Gneiss (aplogranitic type). The fair to large amounts of accessory minerals present in these rocks, of which apatite is quoted as an example, are apparently comparable with those in the porphyroblastic rocks.

The granite intrusions so far mapped by Jansen form three plutons and seven cupolas (see Map 1) which most likely merge into one large pluton at depth. The contacts between the granite intrusions and the rest of the Archaean Complex, where observed, are sharp and steep, so that there is no indication of the possible sub-surface extent of the granite at the present time.

The composition of these rock-types, especially of those in the middle of the sequence, is more in keeping with the geochemical requirements of monazite than is the composition of the porphyroblastic granite-gneiss. The possible origin of the monazite from a deep-seated source genetically associated with the regional granitisation, seems on geochemical grounds to be unlikely. On the other hand, the suite of younger syenitic rocks displays very weak radioactivity, both in the rock-types themselves and within the restricted area of their invaded marginal and hood-zones. It is unfortunately impossible to illustrate the distribution of the dykes and apophyses of the intrusives on Map 1, but Jansen's mapping has shown them to be very restricted. It is possible that similar intrusions occur nearer to the area of monazite mineralisation, in parts which have not yet been mapped in detail. Excepting this possibility for the present, however, the distance of the primary monazite deposits from the known intrusions and their area of influence minimises the likelihood of a genetic relationship between them.

The restriction in the number of mineral species and their high concentration in either phase of mineralisation in these deposits suggests very strongly that they originated from a concentrated residual source, in preference to a magmatic source which would have given rise to a suite of hydrothermal minerals of more general composition and distribution. The points which arise are the following:-

1. Whether the two phases of mineralisation have a common origin or not;

2. Whether the emanations which promoted the processes of granitisation promoted the formation of the economic minerals as well as the rock-forming minerals;

3. Whether the magmatic stage in which the regional granitisation culminated at depth, could support the differentiation and associated processes necessary to give rise to deposits of this nature and composition;

4. Whether the tectonics preceding the phosphate mineralisation were related to the emplacement of the syenitic suite of rocks;

5. Whether the tectonics preceding the oxide and sulphide mineralisation were related to the emplacement of the syenitic and granitic suite of rocks.

Both favourable and unfavourable arguments can be advanced for mineralisation from either source, but in the opinion of the author the evidence is yet too scanty for a definite decision to be made. The problem of origin is best left to conjecture until more evidence is provided by further detailed surveys of the area.

B. Depth and Agents of Mineralisation

In attempting to assess the depth at which mineralisation took place, it should be borne in mind that there is a considerable lapse in time between the formation of the Archaean Complex or the emplacement of the Cape granite plutons, either of which may have given rise to the mineralisation, and the deposition of the Nama System. During this time interval a great deal of rock has no doubt been removed by erosion. Considering that the ore-bodies occupy positions in the mobilised zone of the granite-gneiss, it is reasonable to assume that the contact with metasediments was not far distant, and that the granite-gneiss here was overlain by a reasonable thickness of metasediments. There is nothing to suggest that the cover of rocks which underwent granitisation was any thinner than that observed elsewhere in the area. This is, however, only indirect evidence of the depth of mineralisation, and for more definite criteria it is necessary to return to the features exhibited by the ore-bodies themselves.

The alteration features in the granite-gneiss, the textures, metallic minerals and general features of the ore-deposits, when compared with the gangue minerals, ore-minerals, ore-texture and characteristics suggested by Grout (1932, pp. 426-427) and Lindgren (1933, pp. 529-533, 543-544, 637-643) seem to indicate a depth of hydrothermal action between the Mesothermal and Hypothermal Zones. The granite-gneiss in which the mineralisation took place bears all the indications of being near the metasediments on Steenkampskraal, but shows on Roodewal and Uilklip the better-defined structures and composition characteristic of the rock some distance away from any such contact.

The nature of the alteration is typically that produced by hydrothermal solutions, and the presence of strengite and jarosite on Roodewal is an indication of the high temperature and pressure under which they were introduced. The phosphate mineralisation in all likelihood proceeded from the same source as these solutions. The distinct replacement features and sharp contacts generally existing between the altered wall-rock and the phosphate minerals, however, suggests a definite interval between the alteration and mineralisation processes.

Regarding the earliest-formed minerals themselves, zircon and apatite are usually associated with high temperature veins or pegmatites (Lindgren, 1933, pp. 763-764). Monazite in quantity has been classed up to the present as a pegmatite mineral. Fluorite is a "persistent mineral" (Lindgren, 1933, p. 90) and cannot be considered as diagnostic.

Since this deposit is definitely not pegmatitic in character, these minerals have probably been introduced by hydrothermal solutions. The volatile nature of some of their constituents ($PO_4^{\equiv}$, F^-) suggests that a vapour phase might also have been present. This may be supported by the fact that the ore-contacts are very much sharper in the upper, probably cooler, portions of the deposit, where somewhat less pressure than in the lower portions would have prevailed; any vapour present here would be prone to condense more easily than at lower levels. The fine, even grain of the phosphate minerals may also indicate rapid cooling. Niggli has relegated the formation of the rare earth minerals to the pneumatolytic-pegmatitic stage of magmatic ore-formation (1929, pp. 15, 36-37, 39).

The introduction of magnetite and the primary sulphides into the already crystalline "phosphate ore" may have been brought about by mineralising solutions or vapours, as suggested by Brown (1950, pp. 20-21). The complete sequence of replacement in the order magnetite, pyrite, chalcopyrite and covellite corresponds to either process, whether regarded from the point of view of hydrothermal paragenesis or vapour metasomatism in order of decreasing and increasing Specific Gravity (Brown, 1950, pp. 20-21). The "phosphate ore", prior to replacement by the oxides and sulphides, was compact, yet there had been sufficient space for all the minerals to tend towards idiomorphism. The ore is therefore judged to have been reasonably porous, and the fact that the oxides and sulphides are more widely dispersed in the wall-rocks than are the phosphate minerals cannot be used as an indication of replacement by vapours in preference to solutions. The close association between the metallic minerals and quartz seems to indicate that this mineralisation has proceeded through the medium of siliceous solutions. Moreover, the presence of siderite as the last-formed mineral, shows that hot solutions were still present at the end of the mineralisation process.

X.- Summary and Conclusions

A. Results of Investigation

The radioactive phosphate of the cerium earth metals, monazite, occurs with apatite, zircon, primary and secondary iron and copper minerals in epigenetic bodies and lodes in the Archaean Complex. Geographically, the occurrences are near the southern extremities of the Kamiesberge where they disappear beneath the Knersvlakte peneplane, leaving an inselberg topography controlled by the semi-arid climate. Geologically the area is one in which the Archaean basement has been exposed through the removal of overlying Nama and younger sedimentary formations, some of which remain as outliers.

The Archaean rocks, because they present certain features which are inconsistent with the intrusion of primary granites into metamorphic rocks, are believed to have formed by regional granitisation. They are represented by granulite, metaquartzite and aplogranite which have been correlated with the Malmesbury Formation, and porphyroblastic granite-gneiss, which is regarded as representing the highest grade of granitisation. Small occurrences of pyroxenite, anorthosite and lamprophyre, and veins of pegmatite and quartz also form part of the Complex.

On Steenkampskraal, mineralisation has taken place in the altered rock of a shear-zone. It was represented firstly by the introduction of zircon, monazite and apatite. After these minerals had crystallised, renewed shearing took place on a small scale, and this was followed by the introduction of iron and copper minerals, probably through the medium of siliceous solutions. The quartz has largely recrystallised at some time post-dating its introduction. On Uilklip and Roodewal exactly the same minerals occur; they also favour the replacement of altered porphyroblastic granite-gneiss, but are not restricted to zones of shearing.

The ore-bodies are characterised by their distinct replacement of the altered granite-gneiss, by the equigranularity of their minerals, and by the perfect mosaic texture formed by the phosphate minerals. None of the minerals shows any unusual properties, except for monazite which is sometimes polysynthetically twinned parallel to the basal pinacoid. This rare form of twinning probably resulted from the shearing of the "phosphate ore". The discolouration of certain monazite crystals is attributed to the physical disruption of the crystal lattices.

The phosphate minerals are replaced to a variable extent by the later iron and copper minerals and the accompanying quartz. Where this replacement is not extreme, the phosphate minerals maintain a combined proportion of 80% or more of the ore; apatite tends to increase, and zircon to decrease in proportion, in depth.

The truncation of the Roodewal deposit by the pre-Nama erosion surface clearly reveals that the mineralisation is older than the Nama System, and fossil detrital deposits of zircon, monazite and titaniferous magnetite have been located in the Kuibis Series.

Other primary occurrences of radioactive minerals in the area are attributed to the apparent enrichment of the granite-gneiss in zircon and monazite, and of a recrystallised quartz vein in monazite and xenotime. The first two minerals are also present in "black sands" which have been concentrated from the mechanical disintegration products of the granite-gneiss. A pegmatite vein contains primary columbite-tantalite which is slightly radioactive.

Other minerals which occur in the area, but not in economic quantities, are fluorite, magnetite and barite. Deposits of gypsum are worthy of further investigation. Underground water is scarce but not unobtainable.

B. Nature of the Mineralisation

The investigation of the monazite deposits was two-fold in purpose. Firstly, a hitherto unknown type of monazite occurrence had to be investigated; secondly, the surrounding area had to be examined so that possible controls for the mineralisation could be established. A knowledge of these controls would assist in the prediction of other areas favourable for mineralisation, after a study of the regional geology had been made. Combining the results of both aspects of the investigation, the following conclusions may be drawn:-

1. The minerals are present in zones of hydrothermal alteration in the porphyroblastic granite-gneiss.

2. This alteration has taken place in rigid granite-gneiss, often faulted or sheared, and it must therefore post-date the formation of the Archaean Complex.

3. The radioactive and other ore-minerals clearly replace the alteration products in these zones and must therefore post-date their formation, even if only by a short period.

4. The total period of mineralisation was sufficiently long for the "phosphate ore" to crystallise and then become fractured and brecciated by renewed shearing, after which the oxides and sulphides were introduced.

5. Mineralisation by zircon and the phosphate minerals elsewhere than on Steenkampskraal, Roodewal and Uilklip takes the form of metasomatic enrichment in mylonites, a recrystallised quartz vein and in granite-gneiss.

6. The mineralisation post-dates the emplacement of pegmatites in the Archaean Complex.

7. The mineralisation is pre-Nama in age. Erosion of the primary ore-deposits in the surrounding Complex has given rise to fossil placer deposits containing detrital monazite and zircon in the lower members of the Nama System.

8. In every case, the mineralisation has taken place in the originally mobilised zone of the granite-gneiss near its contact with the metasediments.

9. The mineralisation seems to be associated with marked deviations from the normal trend of the foliation in the granite-gneiss. These are distinct structures which should not be confused with the locally contorted features that are occasionally encountered at the contact between the granite-gneiss and the metasediments.

The formation of the monazite and the other minerals associated with it can be dated, but not referred to a definite source. Two possibilities that may be considered, however, are:-

(i) The mineral constituents may have been concentrated at depth during a magmatic stage following the regional granitisation, and may have been released subsequent to the consolidation of the Complex, when rupture of the crust took place after internal pressure had been reduced through cooling;

(ii) The mineralisation is connected with the intrusion of the granitic and syenitic rocks west of Bitterfontein, but which have not yet been observed in the immediate vicinity of the monazite deposits.

The evidence at the moment is insufficient to relate the mineralisation to either possibility.

Summarising the information which has been gained from the investigation, the following seem to be the controls which will be of practical use in locating further primary occurrences:-

1. The deposits will be pre-Nama in age i.e. they will only occur in the Archaean Complex;
2. They will probably occur in the granite-gneiss near its contact with the metasediments;
3. They are likely to favour areas of hydrothermal alteration;
4. They will probably favour weaknesses in the crust, where there are unusual departures from the regional structure;
5. They are likely to be associated with tectonic features like fault-zones, mylonites etc. in the Complex.

It should be borne in mind, however, that the faults and shear-zones are not confined to the porphyroblastic granite-gneiss, but affect the metasediments as well. There is no reason, therefore, why a mineralised fault-zone could not occur in the metasediments as well as in the granite-gneiss. All exposures of the crystalline basement are therefore potentially mineralised areas until detailed mapping and radiometric traversing prove them to be otherwise.

There is, as yet, too little evidence to enable predictions to be made about the probable position of fossil placer deposits in the Nama System, except that they are likely to be associated with coarse-grained, ferruginous Kuibis sediments.

C. Geological History of the Area

Reviewing all the information derived from the investigation, the following is the probable sequence of geological events which affected the area:-

1. Orogenesis compressed the Malmesbury sediments into steeply folded and contorted strata, and depressed them to a level where they were subjected to regional granitisation.

2. The metamorphism of the sediments proceeded in two stages. The first gave rise to granulite, metaquartzite and aplogranite, and the second to porphyroblastic granite-gneiss. The processes involved were mainly recrystallisation and enrichment in potash.

3. Mobilisation of the more highly granitised rocks led to the formation of a magmatic phase in depth, during the existence of which certain differentiates were formed.

4. The Complex became rigid. The anorthositic and pyroxenitic differentiates crystallised as interfoliated bodies. The rest of the differentiates were emplaced at intervals, the youngest being represented by the bodies which are transgressive to the present foliation.

5. After consolidation, tectonics gave rise to the pre-Nama faults and shear-features.

6. Hydrothermal alteration of the granite-gneiss took place, particularly along zones of fracture.

7. Zircon, monazite and apatite were introduced, possibly from the same source as the solutions which were responsible for the hydrothermal alteration of the wall-rock.

8. Minor shearing of the "phosphate ore" was followed by oxide and sulphide mineralisation along the same shear-zone. The metallic minerals replaced the wall-rock more extensively than the phosphate minerals.

9. Post-mineralisation faulting of uncertain age followed. The recrystallisation of quartz in the ore may be due to these movements.

10. The surface of the Complex was roughly peneplaned under climatic conditions similar to those existing at present.

Sub-aerial consolidation of boulders, detritus and grit derived from mechanical weathering of the underlying rocks took place not far from their source. This was followed by sub-aqueous deposition, as indicated by the presence of ripple-marks, current bedding and sorting in the finer-grained sandstone, and the thin, intercalated shale bands which terminate the Kuibis succession.

11. A distinct period of time followed the deposition of the Kuibis sediments, during which they were exposed and locally weathered. Small boulders and pebbles of quartzite formed a thin, overlying conglomerate. The succession of Schwarzkalk rocks was laid down conformably on the Kuibis Series, at first alternately sub-aerially and sub-aqueously, giving rise to the limestone and intercalated calcareous shale. The deposition of the finer-grained, well-laminated shales then took place sub-aqueously. The succession becomes more arenaceous towards the top until the conglomerates which begin the Middle Stage are reached, indicating a decrease in sorting, and therefore a relative lessening in depth. The conglomerates are followed by more arkose and shale, which suggests a reversal of the foregoing conditions.

12. After the consolidation of the entire succession, the crust was subjected to buckling stresses which found expression in the development of one system of parallel fold-axes trending NNW.- SSE., and another, subordinate, system trending at right angles to the first. The main system gave rise to long synclinoria and anticlinoria, some of which commence very abruptly and are almost monoclinal, and attenuation of the strata took place along the steeper limbs of these folds. The second system caused the pitching of the folded strata to north and south, and the formation of troughs and canoe-folds, separated by transverse ridges. The tectonics were accommodated in the crystalline basement by slight flexure; most of the folding was taken up by differential movement along small faults and joint-planes, and along the old basement surface subjacent to the Nama System, which became transformed into flaser-gneiss. These tectonics probably took place while the sediments were still fairly plastic, thereby allowing their attenuation; nevertheless, the faults in the area, especially the dip-faults, have clearly resulted from the failure of the sediments to accommodate, by folding, the effects of

the stresses imposed upon them. The prominent north-south step-faulting of the Nama System and contemporaneous infilling of the fault-zones by vein quartz that has been recorded by Rogers (1912, pp. 14, 31), Brink (1950, pp. 204-208) and Jansen (1955) west of this area, are probably related to this period of tectonics.

13. The folded strata no doubt provided strong relief, and post-tectonic erosion removed much of the less resistant Schwarzkalk Series before the deposition of the Cape or Karroo Systems took place. Peneplanation probably preceded the deposition of each of these Systems, as the angular unconformity is quite distinct in the Escarpment to the east.

14. The dolerite dykes were intruded and cut the present directional features of the crystalline basement, partially intruding the Kuibis Series. They do not appear to have undergone post-emplacement movement, and therefore probably post-date the Nama tectonics.

15. Erosion of the area persisted until Tertiary (?) time, when silcrete was formed on Schwarzkalk shale, on dip-slopes of Kuibis quartzite, and on the exposed Archaean Complex. The silcrete, therefore, lay unconformably on a somewhat irregular surface which at present decreases in altitude from north-east to south-west, but which may have been more level at that time.

16. Corresponding joints in the silcrete and the underlying Kuibis rocks suggest post-Tertiary (?) flexure, which might also have involved gradual tilting to the south-west.

17. Subsequent erosion removed a great deal of the silcrete and the underlying rocks. A youthful landscape characterised by alternating ranges of hills and deep valleys developed, but a Recent rise in sea-level caused the latter to become choked by locally derived Recent deposits, and so gave rise to the present inselberg topography. The drainage system has recently become rejuvenated, probably by a lowering of sea-level.

XI.- Suggestions for Future Geological Work in the Area

Certain of the results obtained through geological and geophysical work have clarified the general impression that radioactive minerals are very common in Namaqualand. It is felt, therefore, that a contribution has been made in assessing the economic possibilities of an area in which comparatively little of the detailed geology is known.

It is considered that the continued search for radioactive and other minerals would not go unrewarded, if it were based on considerations of regional structure and stratigraphy similar to those which apply to the known monazite deposits. Until sufficient geological evidence has been gathered to the contrary, the area must remain potentially favourable for mineralisation. The distribution of the various members of the Archaean Complex, with which the minerals may be associated, is not yet accurately known, but to judge from such geological reports as are available, and from reconnaissance trips through the surrounding area, there is no reason to doubt that further deposits of monazite ore do occur. Rumours that further deposits are known to the local inhabitants are considered, therefore, not to be without foundation.

If the search for prescribed materials is to be continued, factors of economy and efficiency must be taken into account. The planning of the work, and the interpretation and assessing of the radiometric results requires the use of accurate and detailed geological maps, so that anomalous radiation can be distinguished from normal radiation. In the past the progress of geological mapping for this purpose has been retarded by the necessity of surveying by plane table, which requires the erection of well-placed secondary beacons in dissected country, dry weather and reasonably good visibility. Had aerial photographs of the area been available, the same work could probably have been done in a third of the time. They would also eliminate the need to map topocadastral information for the benefit of the C.A.R.G.O. unit operator, who requires it for the orientation and location of the radiometric traverses. It is suggested, therefore, that future investigations of this nature in unmapped areas be preceded by an aerial photographic survey to ensure greater economy and efficiency in the subsequent field-work.

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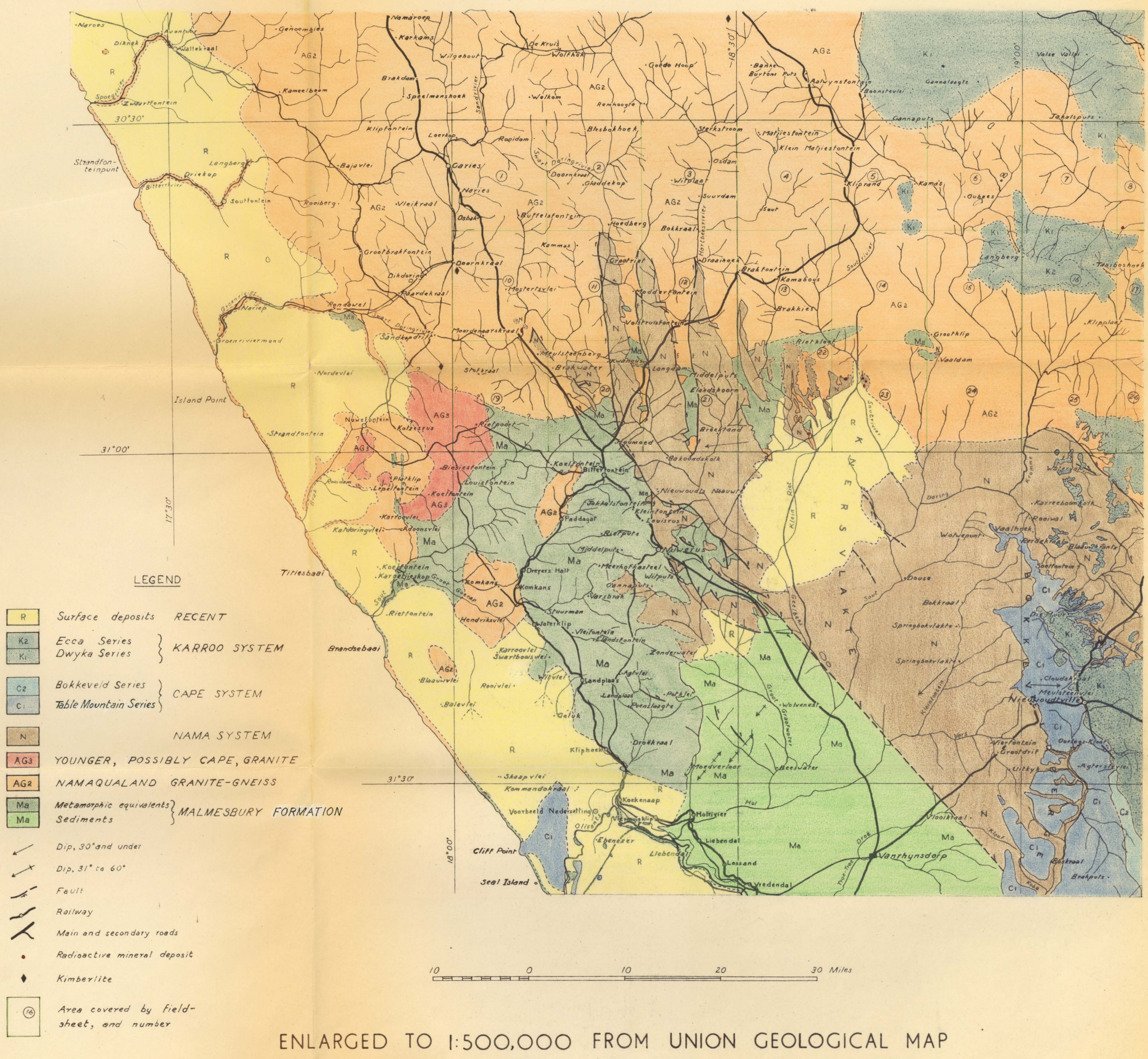
MAP 1

REGIONAL GEOLOGY OF AREA SURROUNDING DEPOSITS



ENLARGED TO 1:500,000 FROM UNION GEOLOGICAL MAP
AND MODIFIED WHEREVER POSSIBLE BY INFORMATION RECENTLY OBTAINED

GEOLOGY OF THE AREA SURROUNDING THE MONAZITE DEPOSITS

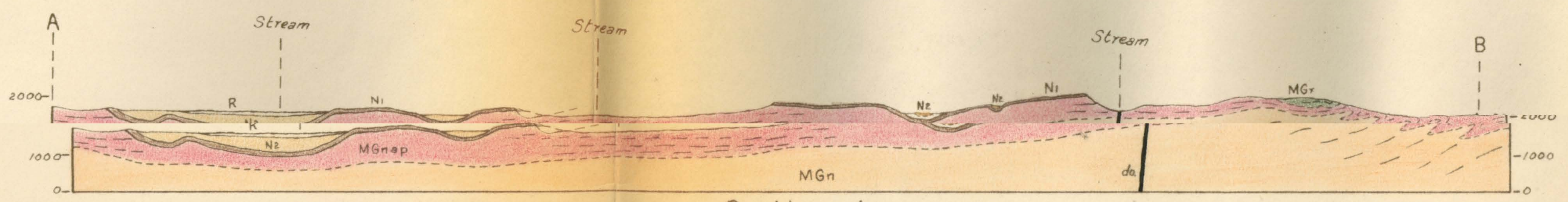
LEGEND

R c	Gravel, clay, sand, gypsum (R); calcrete (c)			RECENT DEPOSITS
T	Silcrete			TERTIARY SYSTEM?
qvn	Quartz vein			
do	Dolerite			
N_2 N_{2R} N_2 N_{2c}	Limestone (N_{2c}), calcareous shale, shale, flagstone, grit, arkose (all N_2), conglomerate (N_{2R})	Lower and Middle Stage	Schwarzkalk Series	NAMA SYSTEM
N_1	Conglomerate, arkose (presence of monazite specially indicated), feldspathic sandstone, sandstone, feldspathic quartzite, quartzite, micaceous shale (all N_1)		Kuibis Series	
Monazite	Ore-deposits of monazite and sulphides, magnetite and barite			
qv	Quartz veins			ARCHAEAN COMPLEX
pet	Transgressive pegmatite			
MSc MGr	Biotite schist (MSc), magnetite-garnet-biotite granulite, biotite-hypersthene granulite, sillimanite-cordierite gneiss (all MGr)	Mafic Granulite Group	Probable granitised equivalents of the Malmesbury Formation	
MQ	Metaquartzite, feldspathic metaquartzite, recrystallised quartz veins, quartz "blows"	Metaquartzite Group		
MGnap	Aplogneiss, aplogranite, interfoliated aplite (all MGnap) and interfoliated pegmatite (pe)	Aplogranite Group		
AUp	Pyroxenite	Palingenetic or Metamorphic Differentiates		
ANa	Anorthosite			
MGn	Porphyroblastic granite-gneiss			

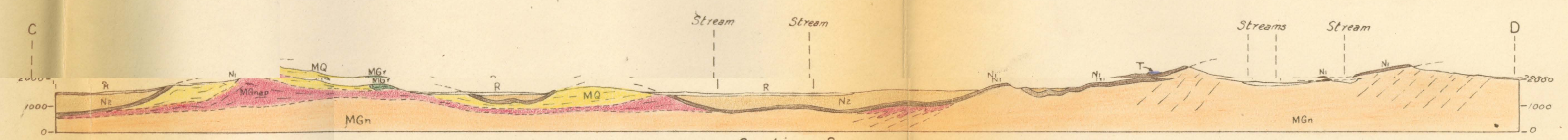
15	Strike and dip of sedimentary strata, with amount of dip in degrees
	Contorted strike and dip of sedimentary strata
+	Horizontal sedimentary strata
	Contorted horizontal sedimentary strata
42	Strike and dip of foliation in crystalline and metamorphic rocks, with amount of dip in degrees
	Direction of horizontal lineation in crystalline and metamorphic rocks
36	Strike and dip of foliation as above, with direction of lineation
65	Strike and dip of foliation as above, with horizontal lineation
✦	Horizontal foliation of crystalline and metamorphic rocks
	Vertical foliation of crystalline and metamorphic rocks
	Contorted foliation of crystalline and metamorphic rocks
84	Shear-zone with direction and amount of dip of shear-plane
F	Fault
	Horizontal fold axis, indicating direction of strike
	Plunging fold axis
● BhWp	Bore-hole, drilled by Government machine, and fitted with wind-pump
Obh	Dry bore-hole, drilled by private machine
● W	Well
• d	Diamond-drill hole
	Ephemeral stream
ED	Dam with earthern wall; water not perennial
▲	Trigonometrical beacon, with name, number and altitude
■	Mine shaft
▨	Mining plant, living quarters etc.
▪	Homestead
	Secondary road
	Farm road, graded
	Farm track

SCALE 1:50,000

1 0 1 2 3 Miles



Section 1



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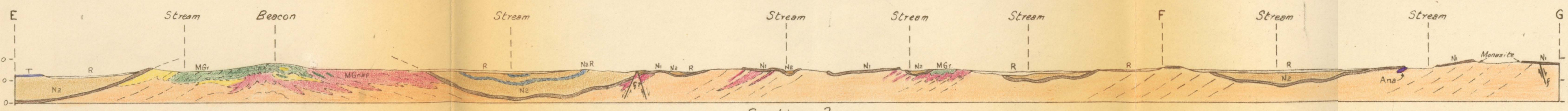


Section 3

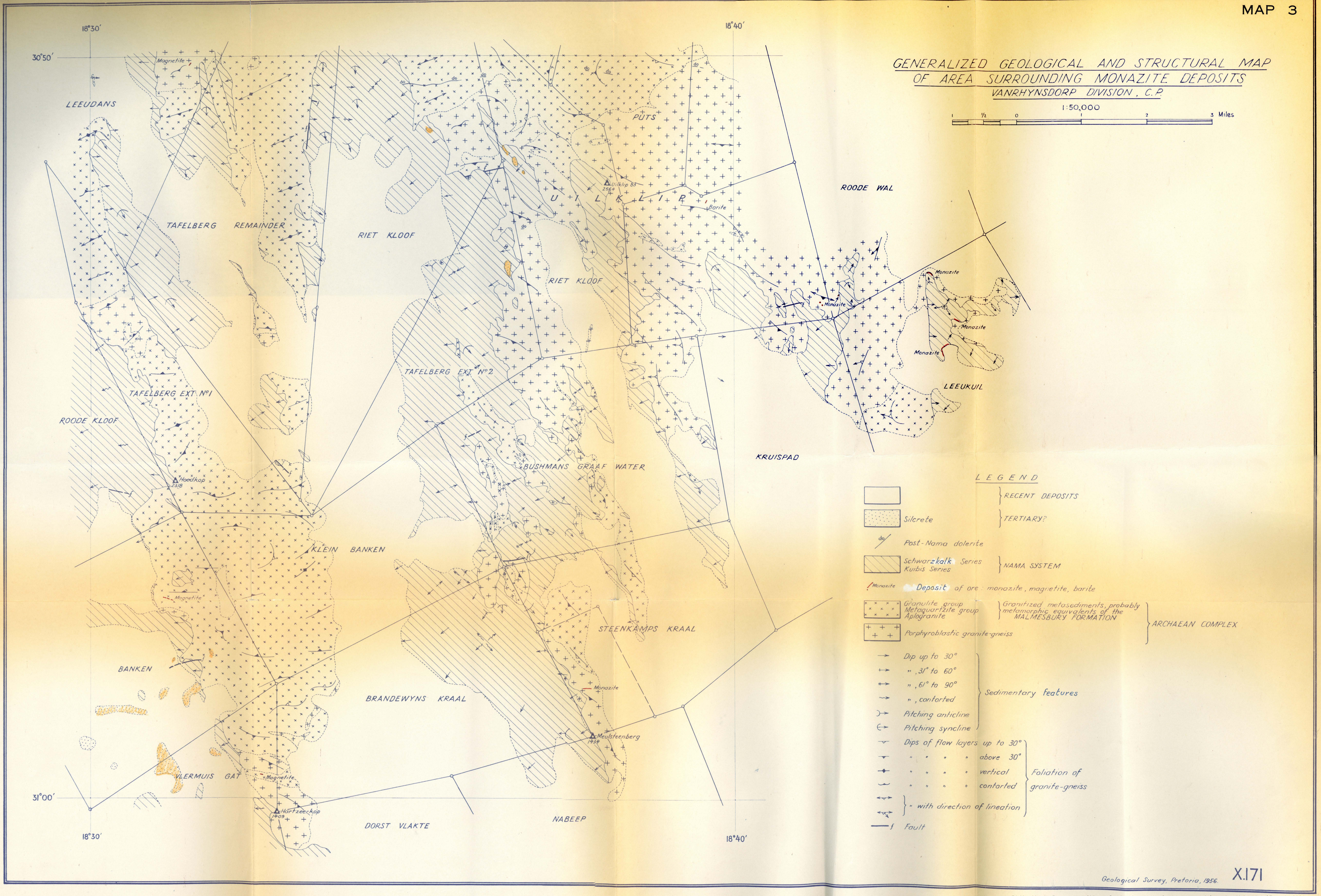
Section 4

MAP 3

GENERALIZED GEOLOGICAL AND STRUCTURAL MAP OF AREA SURROUNDING MONAZITE DEPOSITS

VANRHYNSDORP DIVISION, C.P.

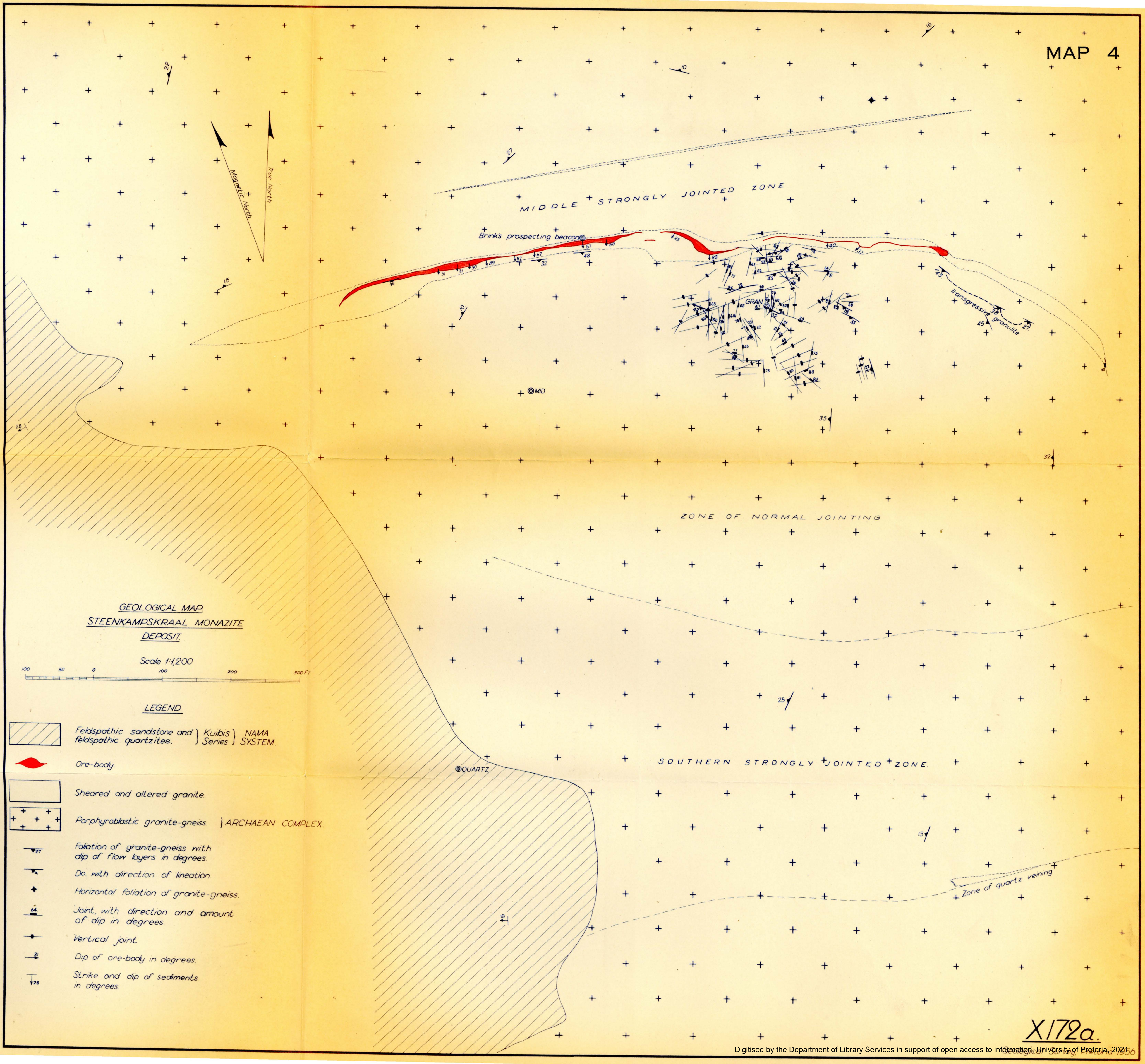
1:50,000



Geological Survey, Pretoria, 1956.

X.171

MAP 4



GEOLOGICAL MAP STEENKAMPSKRAAL MONAZITE DEPOSIT

Scale 1:1,200

LEGEND

▨ Feldspathic sandstone and feldspathic quartzites. } Kuibis Series } NAMA SYSTEM.

Ore-body.

☐ Sheared and altered granite.

Porphyroblastic granite-gneiss. } ARCHAEAN COMPLEX.

Foliation of granite-gneiss with dip of flow layers in degrees.

Do. with direction of lineation.

✦ Horizontal foliation of granite-gneiss.

Joint, with direction and amount of dip in degrees.

Vertical joint.

Dip of ore-body in degrees.

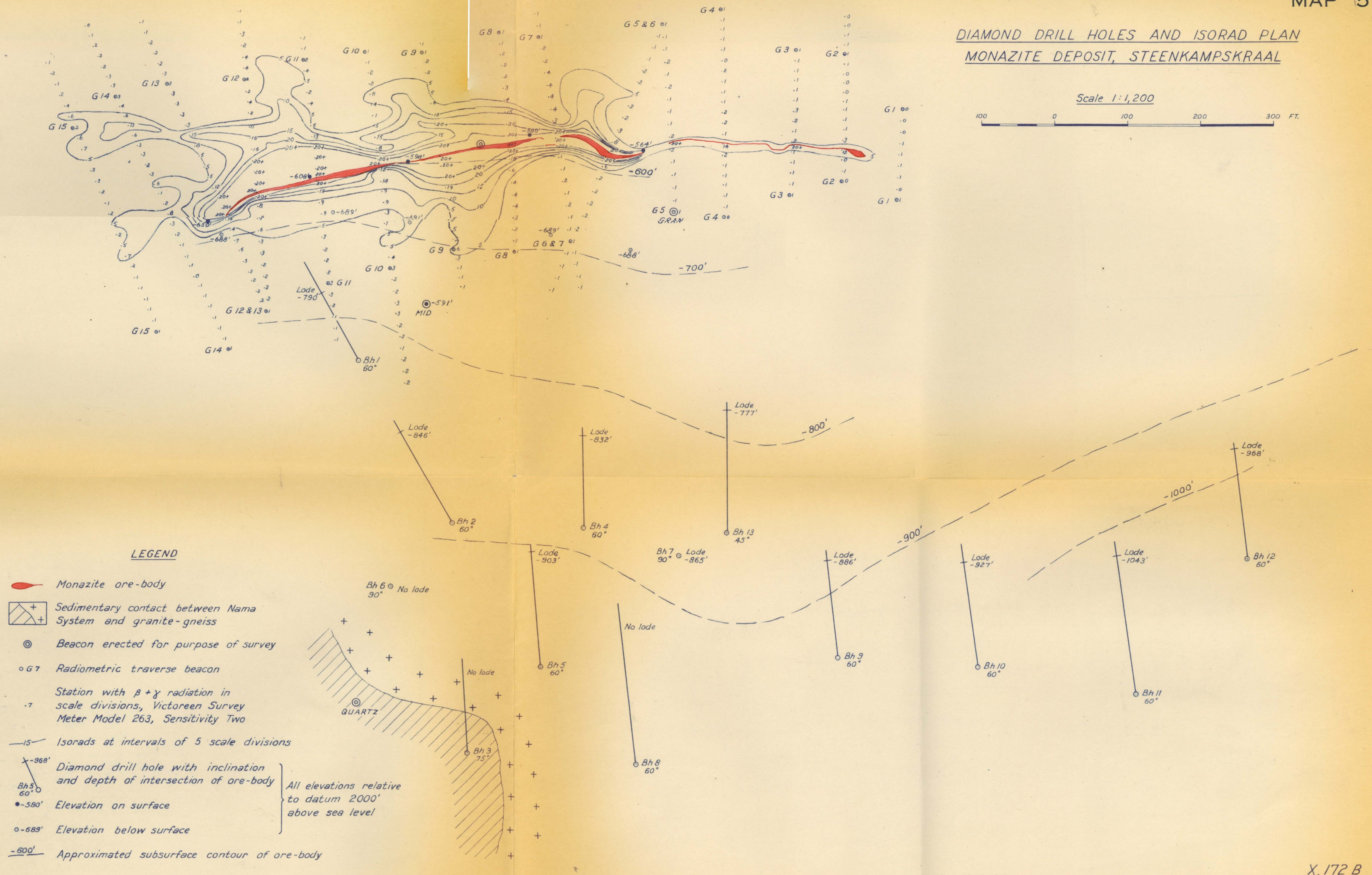
Strike and dip of sediments in degrees.

X172a.

MAP 5

DIAMOND DRILL HOLES AND ISORAD PLAN
MONAZITE DEPOSIT, STEENKAMPSKRAAL

Scale 1:1,200



LEGEND

🟥 Monazite ore-body

▨ Sedimentary contact between Nama System and granite-gneiss

◎ Beacon erected for purpose of survey

○ G 7 Radiometric traverse beacon

·7 Station with β + γ radiation in scale divisions, Victoreen Survey Meter Model 263, Sensitivity Two

—15— Isorads at intervals of 5 scale divisions

Bh 5 60° -968' Diamond drill hole with inclination and depth of intersection of ore-body

●-580' Elevation on surface

○-689' Elevation below surface

All elevations relative to datum 2000' above sea level

-600' Approximated subsurface contour of ore-body

X. 172 B

Geological Survey, Pretoria, 1956

MAP 6

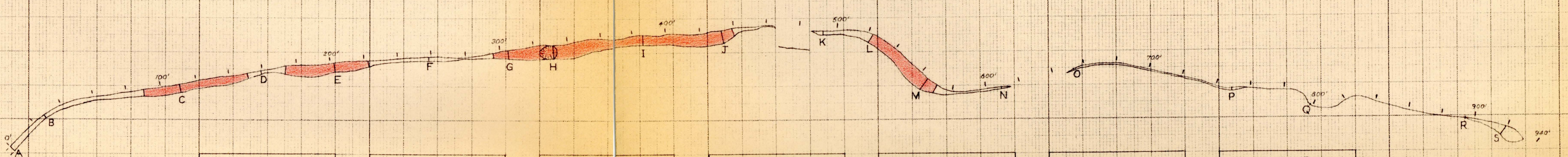
ASSAY SHEET

STEENKAMPSKRAAL MONAZITE DEPOSIT

SCALE 1:609.6

0 100 200 Ft.

SURFACE



Section A			
Sample	Width	% ThO_2	In.%
1	6	5·70	34·20
2	10	4·64	46·40
3	10	5·10	51·00
4	11	5·40	59·40
Total	37		191·00
Correct	19	5·16	98·08

Section B			
Sample	Width	% ThO_2	In.%
1	9	6·58	59·22
2	8	5·78	46·24
3	9	5·53	49·77
Total	26		154·33
Correct	13	5·94	77·17

Section C			
Sample	Width	% ThO_2	In.%
1	8	2·46	19·68
2	8	1·31	10·48
3	10	0·01	0·08
4	10	2·59	25·90
5	11	6·77	74·47
6	9	6·76	60·84
Total	56		191·45
Correct	40	3·42	136·75

Section D			
Sample	Width	% ThO_2	In.%
1	8	3·70	29·6
2	10	3·71	37·1
3	5	4·28	21·4
Total	23		88·1
Correct	18	3·83	68·95

Section E			
Sample	Width	% ThO_2	In.%
1	8	3·70	29·60
2	10	4·95	49·50
3	10	2·33	23·30
4	9	5·75	51·75
5	9	4·48	40·32
6	11	5·46	60·06
7	12	5·46	65·52
8	5	7·09	35·45
Total	74		355·50
Correct	37	4·80	177·75

Section F			
Sample	Width	% ThO_2	In.%
1	8	6·48	51·84
2	10	6·15	61·50
3	10	7·12	71·20
Total	28		184·54
Correct	23	6·59	151·59

Section G			
Sample	Width	% ThO_2	In.%
1	6	6·68	40·08
2	10	6·12	61·20
3	6	6·08	36·48
4	11	5·27	57·97
5	11	6·23	68·53
6	14	7·20	100·80
7	6	6·25	37·50
Total	64		402·56
Correct	59	6·29	371·11

Section H			
Sample	Width	% ThO_2	In.%
1	12	3·06	36·72
2	9	7·28	65·52
3	10	4·78	47·80
4	12	5·79	69·48
5	10	5·93	59·30
6	11	5·60	61·60
7	8	4·56	36·48
8	8	3·33	26·64
9	12	2·94	35·28
10	6	1·53	9·18
Total	98		448·00
Correct	88	4·57	402·28

Section I			
Sample	Width	% ThO_2	In.%
1	10	7·25	72·50
2	11	6·70	73·70
3	10	6·76	67·60
4	13	6·75	87·75
5	9	6·57	59·13
6	8	7·12	56·96
7	10	5·00	50·00
Total	71		467·64
Correct	58	6·59	382·02

Section J			
Sample	Width	% ThO_2	In.%
1	10	6·79	67·90
2	10	6·78	67·80
3	12	6·12	73·44
4	12	7·76	93·12
5	12	6·93	83·16
6	12	8·56	102·72
7	10	6·48	64·80
8	12	5·67	68·04
9	10	5·53	55·30
Total	100		675·47
Correct	71	6·76	479·58

Section K			
Sample	Width	% ThO_2	In.%
1	8	6·79	54·32
2	9	7·04	63·36
3	12	6·57	78·84
4	6	7·35	44·10
Total	35		240·62
Correct	18	6·88	123·75

Section L			
Sample	Width	% ThO_2	In.%
1	8	5·46	43·68
2	10	6·30	63·00
3	10	5·92	59·20
4	10	6·15	61·50
5	12	6·64	79·68
6	9	7·42	66·78
7	12	6·80	81·60
Total	71		455·44
Correct	32	6·42	205·27

Section M			
Sample	Width	% ThO_2	In.%
1	8	6·10	48·80
2	11	5·38	59·18
3	10	5·84	58·40
4	11	5·45	59·95
5	10	6·73	67·30
6	10	7·25	72·50
7	9	4·36	39·24
8	12	3·74	44·88
Total	81		450·25
Correct	42	5·56	233·46

Section N			
Sample	Width	% ThO_2	In.%
1	10	4·72	47·20
Total	10		47·20
Correct	6	4·72	33·04

Section O			
Sample	Width	% ThO_2	In.%
1	6	5·38	32·28
2	6	3·89	23·34
Total	12		55·62
Correct	8	4·64	37·00

Section P			
Sample	Width	% ThO_2	In.%
1	9	2·08	18·72
2	7	2·60	18·20
Total	16		36·92
Correct	10	2·31	23·08

Section Q			
Sample	Width	% ThO_2	In.%
1	5	1·66	8·30
Total	5		8·30
Correct	3	1·66	4·98

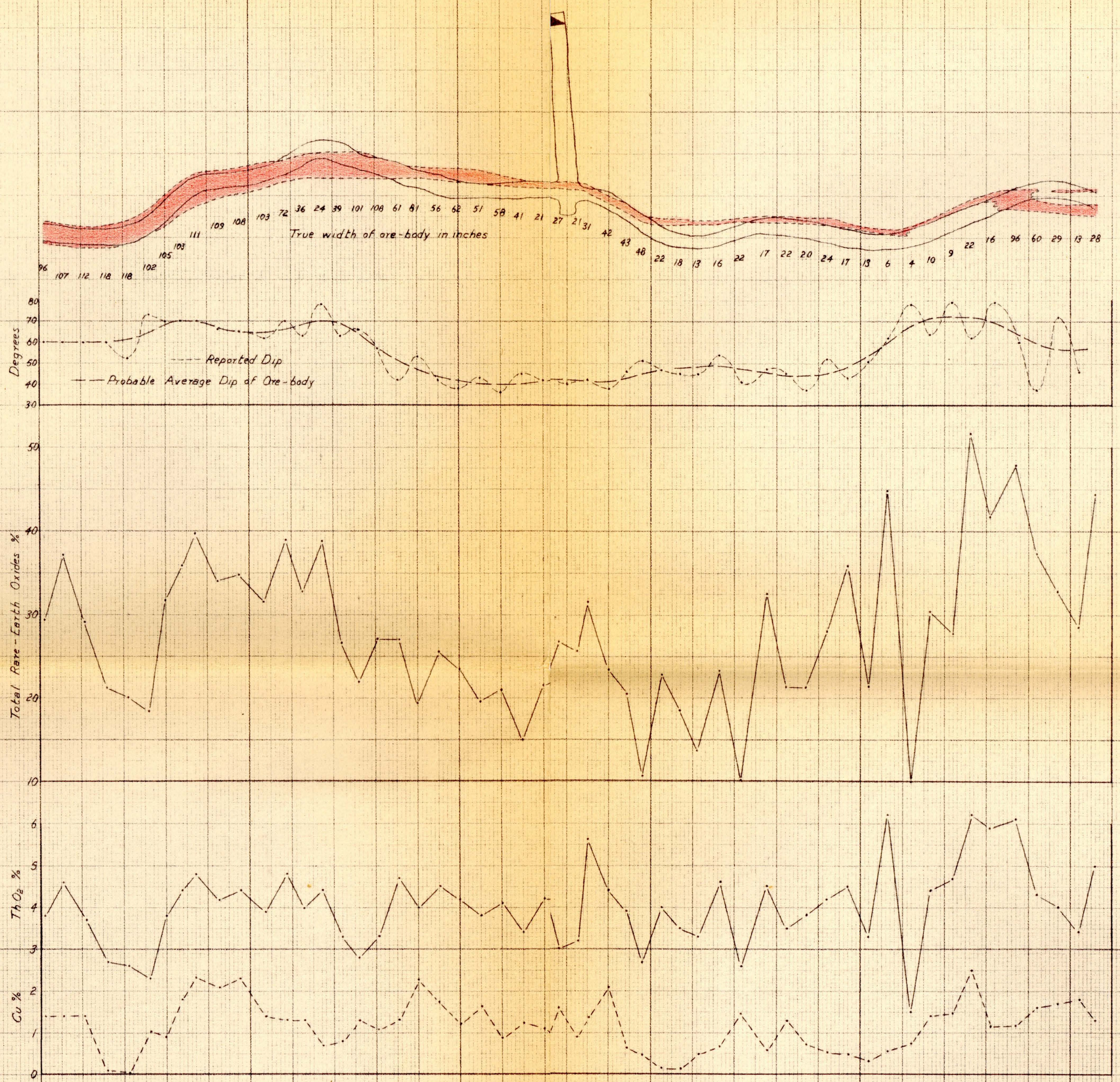
Section R			
Sample	Width	% ThO_2	In.%
1	7	0·90	6·30
Total	7	0·90	6·30

Section S			
Sample	Width	% ThO_2	In.%
1	12	0·50	6·00
2	12	0·34	4·08
3	12	0·42	5·04
4	12	0·70	8·40
5	12	0·44	5·28
6	12	0·46	5·52
Total	72	0·48	34·32

LEGEND

⊥	Outcrop of ore-body with sample channel
🟥	Sections of ore-body with true width above 30 inches
◯	Original prospecting pit

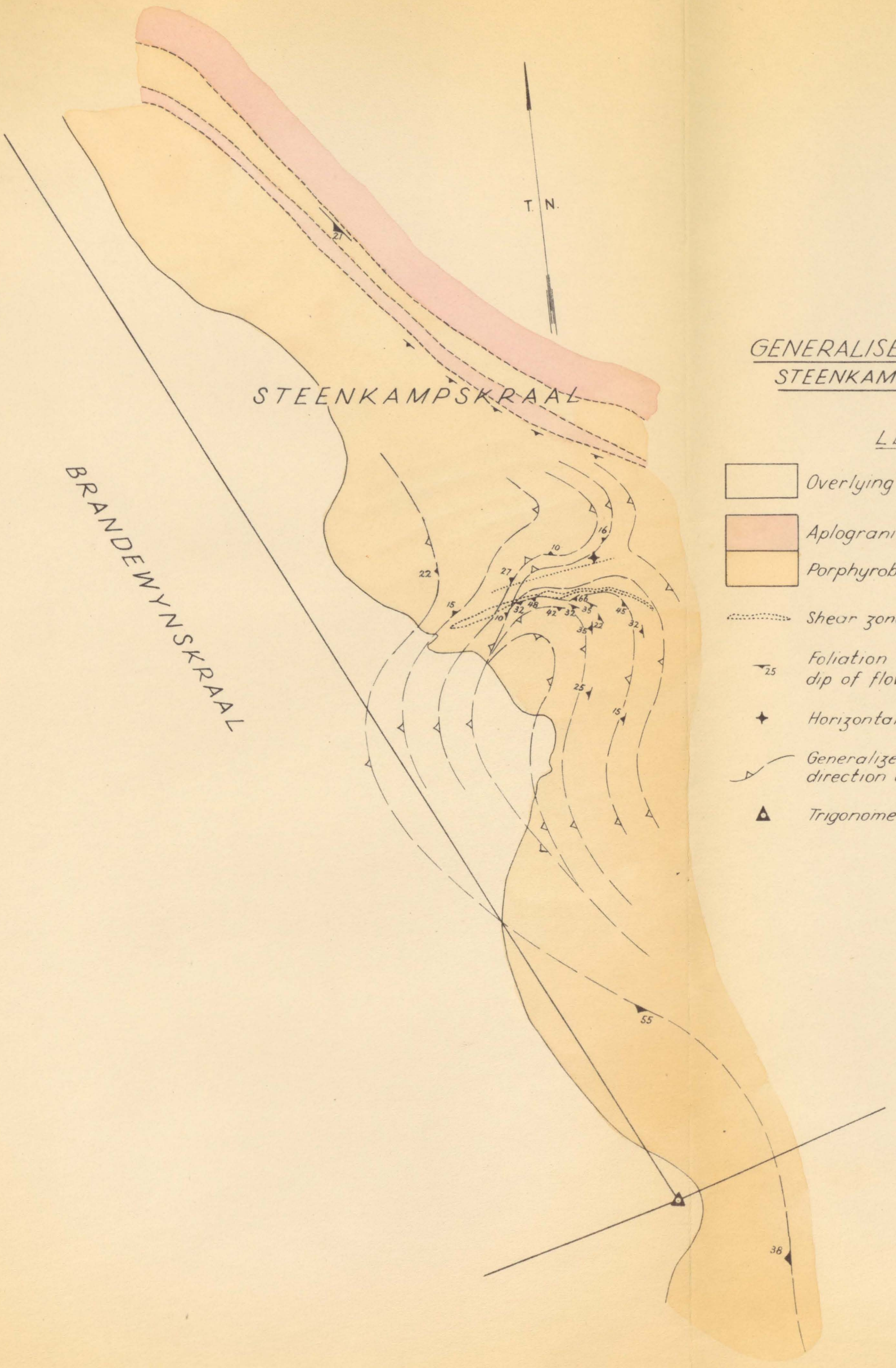
100 FT LEVEL UNDERGROUND



LEGEND

◪	Vertical shaft
⌒	Hanging-wall of cross-cut and drive
🟥	Ore-body. Hanging-wall and foot-wall of ore-body plotted relative to hanging wall of drive

MAP 7



GENERALISED BASEMENT STRUCTURE MAP
STEENKAMPSKRAAL MONAZITE DEPOSITS

Scale : 1 : 10,000

LEGEND

☐ Overlying sediments

🟥 Aplogranite } ARCHAEAN COMPLEX
🟧 Porphyroblastic granite-gneiss } ARCHAEAN COMPLEX

⋯ Shear zone

⌐25 Foliation of granite-gneiss with dip of flow-layers in degrees

✦ Horizontal foliation of granite-gneiss

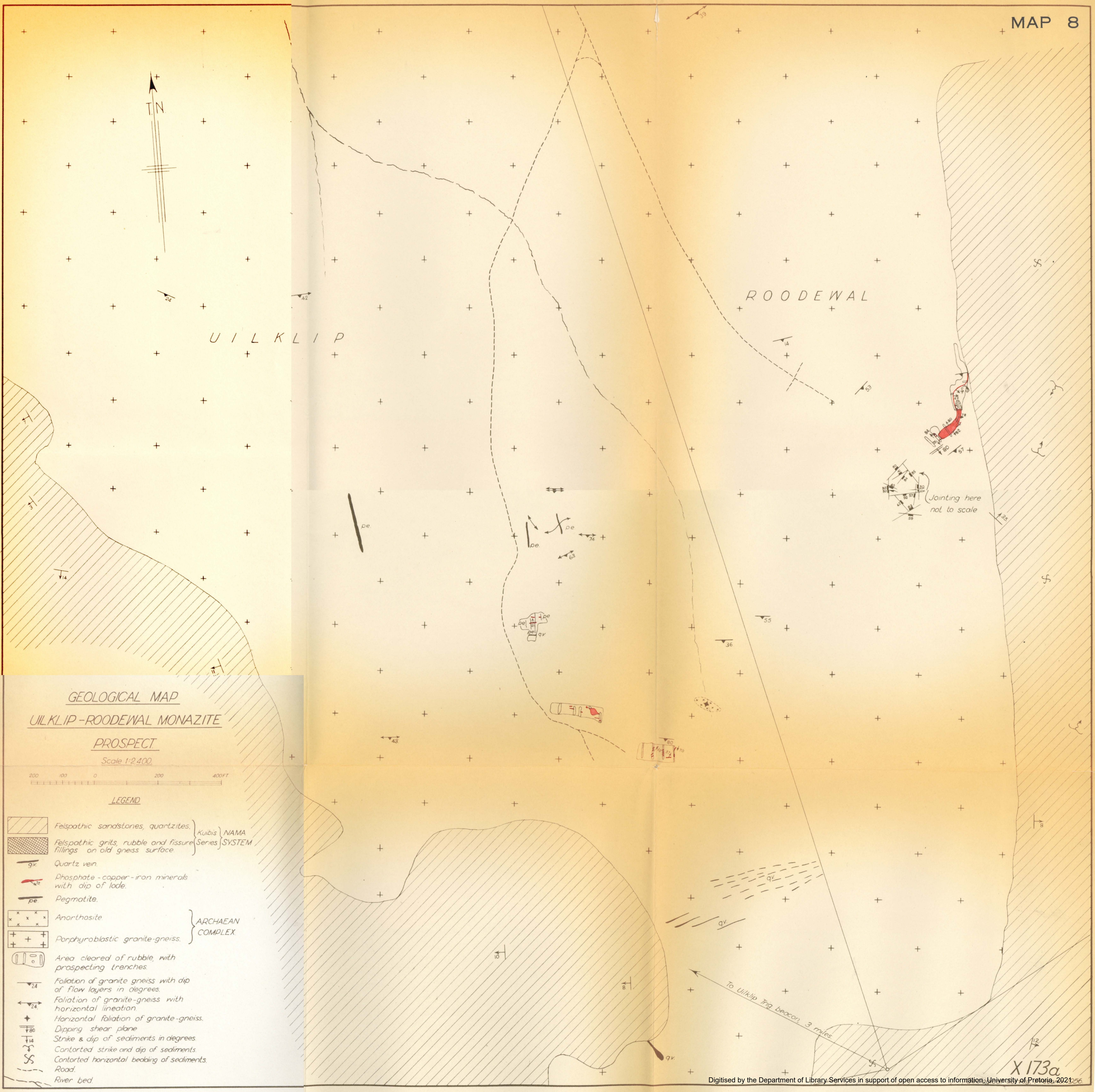
╱ Generalized strike of foliation with direction of dip

▲ Trigonometrical beacon

X207a

Geological Survey, Pretoria.

MAP 8



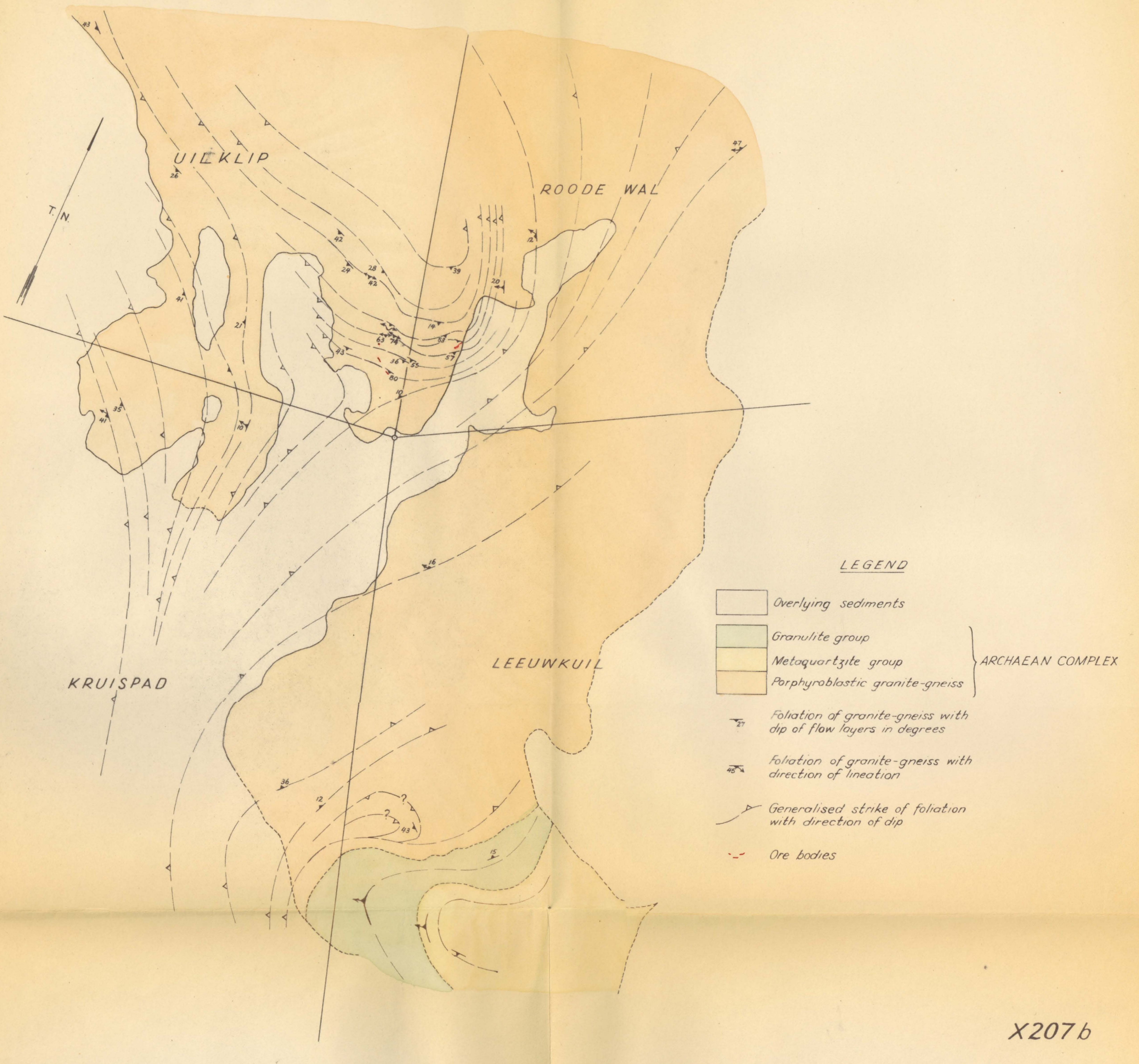
GEOLOGICAL MAP
UILKLIP-ROODEWAL MONAZITE
PROSPECT

Scale 1:2,400.

X 173a

MAP 9

GENERALISED BASEMENT STRUCTURE MAP
UILKLIP - ROODEWAL MONAZITE DEPOSITS
Scale : 1: 20,000



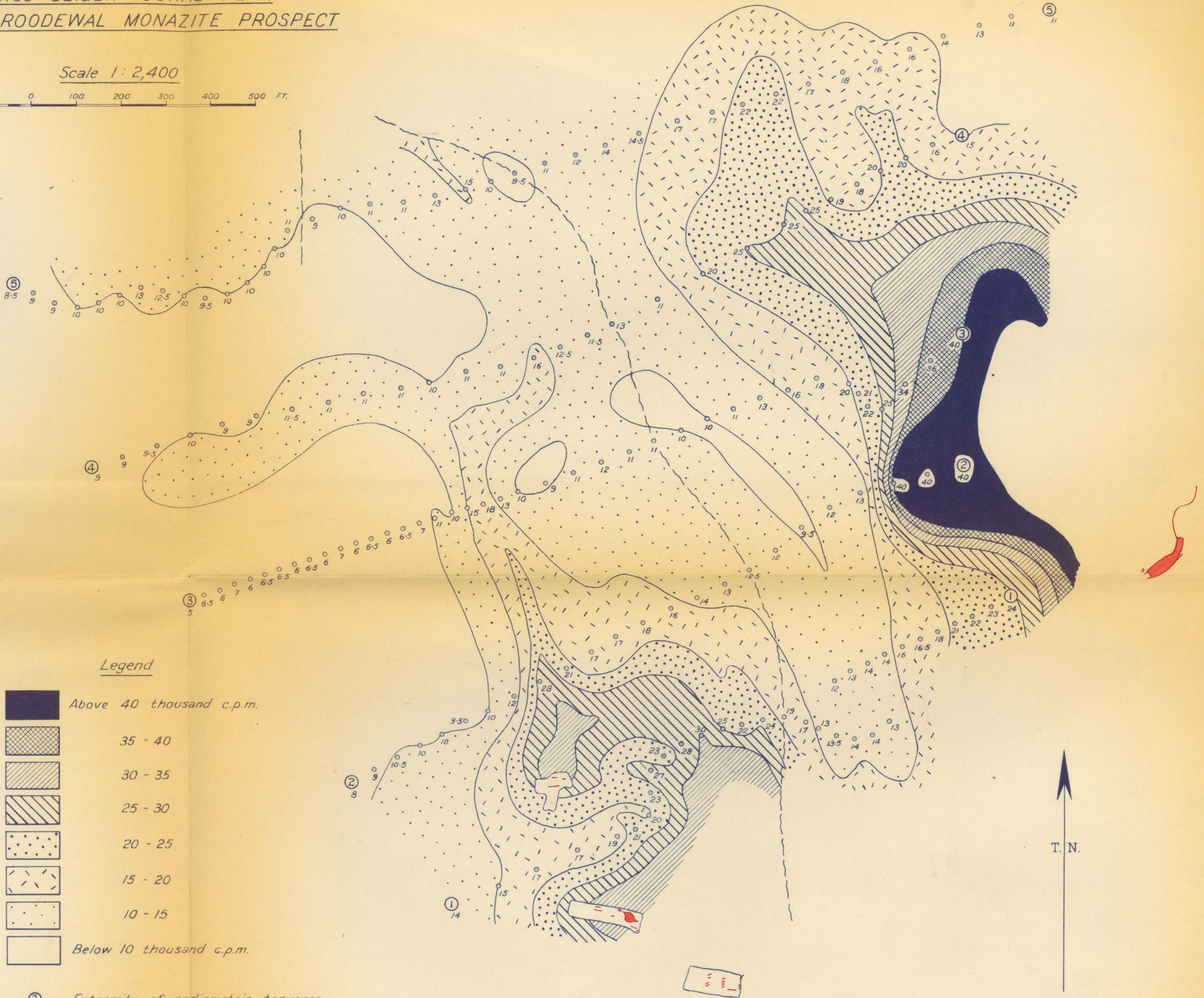
X207 b

Geological Survey, Pretoria
1956

MAP 10

CARGO GEIGER ISORAD PLAN
UILKLIP - ROODEWAL MONAZITE PROSPECT

Scale 1 : 2,400



Legend

■	Above 40 thousand c.p.m.
▩	35 - 40
▨	30 - 35
▧	25 - 30
⁙	20 - 25
⁄	15 - 20
·	10 - 15
☐	Below 10 thousand c.p.m.
③	Extremity of radiometric traverse
●	Phosphate - copper - iron minerals
— — —	River-bed

X.173 B