THE
CARBONATE MEMBER
OF THE
PALABORA IGNEOUS COMPLEX

- R.F. BOUWER -

Summary of a thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy at the University of Cape Town.

May, 1957.

The objects of the thesis are to present facts which were gathered during an exploration programme of the carbonate member of the Palabora Igneous Complex, and thus to attempt to dispel the sceptisism with which many geologists still regard the idea of a magmatic carbonate rock.

The Complex is situated at latitude 23° 58' south and latitude 31° 8' east in the Northern Transvaal. It is set in granite of the Basement Complex and consists essentially of a roughly circular core of carbonate rock separated from the surrounding granite by nearly concentric zones of desilicated rocks. These desilicated rocks are:-

1. A body composed essentially of magnetite, olivine and apatite, and referred to as 'phoscorite', lying adjacent to the carbonate member;

2. a suite grading from a pegmatitic zone rich in vermiculite and diopside pyroxene to pyroxenite, consisting essentially of diopside pyroxene, which in turn passes gradationally into shonkinite a pyroxenite with potash-felspar;

3. and syenite composed of potassium-rich microcline with subordinate pyroxene and amphibole.

Numerous carbonate veins arranged radially with respect to the carbonate member cut the other members of the Complex. A swarm of dolerite dykes not related to the igneous activity of the Complex occur.

The carbonate member is in sharp contact with the phoscorite and contains inclusions of the latter in its peripheral portion. The phoscorite is in turn in sharp contact with the pegmatitic zone of the pyroxenite suite.

The relation of the shonkinite to the syenite is usually gradational, but is also occasionally fairly sharp. The granite-syenite contact is intrusive.

Surveys show that radioactivity, except for that due to transported material, is confined to the carbonate member. Radioactive material is best concentrated in irregular zones in the central part of this body. These zones show a tendency to be elongated in a NW - SE direction. If any differences of radioactive normal exist between the other members of the complex the instruments used were not sufficiently sensitive to show this.

The carbonate member is a coarse- to medium-grained magnesium-rich calcium carbonate rock. The following minerals are macroscopically recognizable in it:- magnetite, apatite, chondrodite and olivine, and various copper sulphides. At surface, malachite, azurite, chrysocolla and covellite are seen. Serpentine occurs frequently.

It is characterised by a distinct vertical mineral banding. It is generally massive but has joints and fractures suggestive of tension. Jointing and brecciation reach their maximum development towards the centre of the carbonate member. Copper sulphides and serpentine are the cementing materials of the breccia. A contour diagram shows the dominant direction of jointing to be north-east. The joints all dip steeply. Although the copper mineralization suggests enrichment along earlier formed joint planes a contour diagram of the copper bands show them to dip steeply, but only an insignificant number follow the strike of the joints which are often formed on planes of weakness now represented by copper mineralization.

The carbonate veins are not radioactive but are otherwise identical to the carbonate member and carry essentially the same mineral assemblage.

In thin section the magnesium-rich calcium carbonate is coarse-grained and has a holocrystalline hypidiomorphic texture. It consists of a completely crystalline intergrowth of dolomitic-calcite.

Apatite occurs as well-formed euhedral prismatic and tabular crystals. These are often bent and strained. The apatite appears to be an early formed constituent.

Chondrodite and olivine are observed as subhedral crystals showing polygonal outlines. Chondrodite is the more abundant and is easily distinguished from olivine by its characteristic polysynthetic twinning and pleochroism. It is suggested that they are early formed minerals after apatite but before the bulk recrystallization of calcite.

Phlogopite and biotite are replaced by copper sulphides and occur as inclusions in magnetite.

Baddeleyite is entirely subordinate as black flattened prismatic crystals of adamantine lustre. They are often twinned. The presence of baddeleyite in the carbonate member suggests a temperature of formation above 600°C.

Pleonaste spinel, showing typical rhombic outlines, occurs as inclusions in magnetite and calcite. It is an early formed mineral. Minor amounts of fluorite replace calcite. Two varieties of serpentine are recognized.

Magnetite is the most abundant opaque mineral and occurs predominantly as large coarse-grained masses while specks and grains, showing cubic outlines, are common. It is replaced by the sulphides. Normally magnetite replaces all the transparent minerals, but in the case of calcite overlapping crystallization is observed. Spectrographic and chemical analyses show the magnetite occurring at depth in the carbonate member to be low in titanium content. This is in contradistinction to the magnetite in the adjacent phoscorite where the average titanium oxide content is of the order 4.48 per cent. The large amount of magnetite present as an ore mineral in the carbonate member indicates a high temperature of formation for the latter. It is suggested that the primary magnetite crystallization followed that of the gangue minerals, but preceded that of uranothorianite and copper sulphides.

Uranothorianite is present as well-formed euhedral crystals on an average 0.3 mm across. Inclusions of calcite and apatite crystals are common. It occurs predominantly in the calcite gangue but also in association with the other gangue minerals and magnetite, but not with the copper sulphides. It shows a marked property of crystallinity. The apatite, ferromagnesian silicates and the main calcite mineralization and magnetite preceded that of uranothorianite.

The sulphides show no crystal form and occur as irregular massive patches and 'schlieren'. Microscopically tiny specks and streaks are seen. These often assume a vein-like form.

Pyrrhotite is one of the less abundant sulphides. Inclusions of apatite and calcite are common in it. Subordinate granular pentlandite residuals, which are present in the pyrrhotite, suggest unmixing of a solid solution at temperatures from 425 to 450°C. The presence of pyrrhotite is indicative of a high temperature of formation. It replaces the gangue minerals and by inference with other magnetite sulphide suites is considered to be early in the sulphide suite.

Chalcopyrite is the most abundant sulphide. It contains residuals of cubanite and pentlandite and occurs in association with bornite, chalcocite and valleriite. Chalcopyrite heals the brecciated portions of the carbonate member without evident signs of replacement. It replaces magnetite. It is associated with pyrrhotite as laths in and as granular intergrowths at the margins of pyrrhotite. This indicates a formation of solid solution between these two minerals at temperatures of about 600°C. The association of cubanite with chalcopyrite suggests contemporaneous crystallization of the two.

Bornite is usually associated with chalcopyrite as granular intergrowths showing mutual relations. Bornite replaces the gangue minerals and magnetite in the same way as chalcopyrite. It is suggested that the bulk of the bornite was formed at temperatures below 500°C.

Chalcocite is far less abundant than chalcopyrite and bornite. Its mode of occurrence is similar to that of the other sulphides but the tendency to occur as irregular veins is far more pronounced. It replaces bornite. Etching shows that it is hypogene chalcocite formed above 105°C.

Valleriite is of widespread distribution mainly as fine laminated aggregates in vein-like form. It replaces the gangue minerals, magnetite and the other sulphides.

The textural relations suggest that the sulphides were the last minerals to crystallize. The paragenetic order in this suite is as follows:- pyrrhotite, pentlandite, cubanite, chalcopyrite, bornite, chalcocite and valleriite. A certain amount of overlapping crystallization is evident. The temperature of formation ranged from above 600°C in the case of pyrrhotite to below 225°C when valleriite was formed.

The paragenetic order of the mineral suite in the carbonate member is normal in that the earlier formed gangue minerals were followed by the metallic oxides which were in turn followed by the sulphides.

The distribution of the economic constituents in the carbonate member shows that a sympathetic relationship exists between the copper and uranothorianite in that the higher grades of copper ore show higher radioactivity. The apatite on the other hand diminishes in content as copper grade increases. This relationship is not a close one but the same boundaries confine both the copper and uranothorianite.

It is possible to subdivide each inclined bore-hole and the adit into an 'inner' and 'outer' zone. The main concentrations of copper and uranothorianite occur in the 'inner' or central irregular zone. This zone is kidney-shaped and elongated in an east-west direction.

The distribution of phosphate values provides the clearest picture. The change from comparatively good to poor phosphate mineralization is clear-cut. The zone of good values passes over into ground showing consistently low values relieved occasionally by areas of sporadic enrichment. Copper is distributed throughout the carbonate member, but is best concentrated in the centre. Uranothorianite is closely confined to this part of the mass. The distribution diagrams show occasional enrichment of uranothorianite in the outer portions of the carbonate member but not to the same extent as copper. The distribution of magnetite bears no relationship to either apatite, uranothorianite or copper.

The highest concentration of copper and uranothorianite is found where jointing and brecciation is prominent.

A vertical bore-hole drilled into the more strongly mineralised zone provided evidence of the continuation of mineralization throughout the total length of the bore-hole of 1893 feet.

Inclined drilling indicates that the carbonate member is probably a plug-like body the walls of which are practically vertical.

The pattern of mineralization can be expected to be vertically disposed and to follow at depth the distribution of radioactivity anomalies obtained at surface.

A statistical study of the distribution of apatite, copper and uranothorianite indicates that the same conditions were favourable for the concentration of copper and uranothorianite, but not apatite.

The results of chemical and radiometric analyses show the proportion of uranium and thorium in the uranothorianite to be quite variable. Thorium, however, always predominates over uranium. A statistical calculation gives a ratio of 1 : 2.81 as a fair approximation.

The paragenesis of the Complex has in the past been explained on the basis of a metamorphic theory or assimilation of limestone. The evidence presented shows that these theories are untenable.

That the carbonate member is of magmatic origin was first suggested by Brandt who deduced the order of intrusion of the complex to be pyroxenite, syenite and carbonate. He concluded, that the mineralization of the complex is related directly to the emplacement of the syenite fraction.

The writer considers that the mineralization of the pyroxenite is more in keeping with normal crystalline differentiation after emplacement. The elements in the phoscorite and the carbonate member were all original constituents of the primary magma which became concentrated in these fractions by differentiation processes.

At Phalaborwa it is probable that assimilation of crustal rocks took place under the influence of either carbonatitic magma or alkali-rich emanations. Probably both were equally active. The evidence suggests that a primary alkalic magma after possible enrichment by assimilation of crustal rocks differentiated at depth into a syenite, pyroxenite, phoscorite and carbonate fraction and that these fractions were emplaced separately in this order. Titanium and phosphorous reached their maximum concentration in the phoscorite fraction. The emplacement of the carbonatite was of a forceful type.

The concentration of magnetite, sulphides and the rare elements in the carbonatite is the result of becoming concentrated in residual liquors during the process of differentiation.

It is suggested that the carbonate-rich fraction was able to take up and carry along some, but not all, the copper and rare elements which crystallized with the carbonatite core. The activity was terminated by the deposition of copper, uranium and thorium from a strongly charged gaseous phase causing enrichment in already consolidated carbonatite.

Comparing the Palabora Igneous Complex with alkali complexes associated with carbonatites in other parts of Africa shows that:-

Carbonatites are intrusive, calcium- and/or magnesium-rich, carbonate rocks of volcanic origin. They are normally associated with several types of undersaturated soda- or potash-rich rocks. They commonly form well-developed ring-structures, in which the carbonatite is normally circular in outcrop and forms the core or central part. The volcanic piles have mostly been weathered-down to the lower part of the original volcanic rock. Intrusive carbonate rocks also occur as cone sheets, dykes and breccia zones. They are characterised by flow structures.

Two main types can be distinguished. These are:-

a. Those in which carbonatite, phoscorite, mixed rocks of ijolitic or pyroxenite type and nepheline syenite and/or syenite occur;

b. where the mixed rocks are absent and carbonatite is associated with nepheline syenite and/or syenite. The Uganda, Southern Rhodesia, Phalaborwa and Spitzkop occurrences are typical of the first type. Those of the Chilwa

Series, Glenover and possibly South West Africa are typical of the second. The exception is Mbeya in Tanganyika where carbonatite only is developed.

The principle accessory mineral assemblage is magnetite, apatite and mica. The presence of pyrochlore and barytes is a common feature of the carbonatites of the Chilwa Series, Uganda and Tanganyika. Common constituents of most are fluorite, rutile, zircon and pyrite. Pyrrhotite is sparingly developed at Mbeya and Magnet Heights. Specks of chalcopyrite occur at Glenover while copper sulphides are prominent at Phalaborwa.

Radioactivity, is a common feature of most carbonatites. Where uranium is present it is always subordinate to thorium. Only at Phalaborwa is uranium of significance.

The prospecting programme shows a higher grade kidney-shaped body of remarkably uniform grade of copper, of the order of one per cent, lying within the carbonatite. The ore reserves are of the order of 50 to 60 million tons per 1000 feet. Accessory products which will be available for exploitation after the extraction of copper include uranothorianite, agricultural limestone, magnetite with a low titanium content and a certain percentage of apatite.

Temperature measurements in one of the vertical boreholes show that rock temperatures are upset by drilling and that a considerable time must elapse before equilibrium is restored. A mean geothermic step for carbonatite of 160 ft / 1°C was obtained eight months after the bore-hole was completed.

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Dear Mr. Vincent

As you have been appointed internal examiner for the thesis submitted by R. F. Bouwer for the Ph.D. degree I am sending you herewith a copy of the thesis. It will be appreciated if you will return the thesis to me when you submit your report.

Yours sincerely,

J. G. Nel...

for/REGISTRAR.

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Thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy at the University of Cape Town.

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ERRATA

Figures 1, 2, 6 and 25.

For carbonatite read carbonate member.

Plate I. - Panoramic view of Loole Kop, looking north.

ABSTRACT

The Palabora Complex, is surrounded by Archaean granite and consists of a central carbonate core with concentric belts of phoscorite, pyroxenite and syenite. Several intermediate rock types are associated with the pyroxenite. Thin carbonate veins and a swarm of younger dolerite dykes cut the complex.

The carbonate member is a magnesium-rich calcium carbonate rock in which magnetite, copper sulphides, ferromagnesian silicates, apatite and uranothorianite occur. Chalcopyrite, bornite, valleriite and chalcocite are the main sulphides present. The mineral association indicates a temperature of formation above 600°C. The paragenetic order is a normal one in which the gangue minerals were followed by the metallic oxides, which were in turn followed by the sulphides.

The carbonate member is radioactive. Radioactivity maps provide an indication of the distribution of uranothorianite at depth.

There is a sympathetic relationship between copper and uranothorianite, which are concentrated in a central zone in the carbonate member. The apatite diminishes in content as the copper grade increases and is mainly concentrated in the peripheral portion of the carbonate member. The distribution of magnetite shows no relation to the other minerals and occurs evenly throughout the carbonate member.

Statistics suggest that the copper sulphides and uranothorianite were deposited under the same conditions, while different conditions were suitable to apatite.

The proportions of uranium and thorium in the urano-thorianite found in the carbonate member are quite variable, but a statistical assessment suggests that a ratio of 1 : 2.81 is a fair average.

The available information supports the conclusion that the complex marks the roots of an ancient volcano and that the carbonate member is of magmatic origin. It is suggested that a primary magma after possible enrichment by assimilation of crustal rocks differentiated at depth into a syenite, pyroxenite, phoscorite and carbonate fraction. These were emplaced separately in this order. The shonkinite resulted from metasomatism of the syenite by pyroxenite. The various differentiates in the pyroxenite suite represent the products of normal differentiation after emplacement.

The concentration of minerals in the carbonate member is the result of them becoming concentrated as differentiation proceeded. The carbonate-rich fraction carried some of the copper and rare elements which crystallized with the carbonate core. The activity was terminated by the deposition of the major portion of copper, uranium and thorium present in the original magma from a strongly charged gaseous phase.

The Complex is of similar type to those occurring in Uganda, Southern Rhodesia and at Glenover. It is most likely of Jurassic age. Radioactivity is a common characteristic of carbonatites. The main differences are found in the accessory mineral assemblage which it is considered reflects the depth of erosion of the volcanic pile.

It is considered that the carbonatite is a feasible low grade copper proposition of large reserves.

CONTENTS

Page

LIST OF ILLUSTRATIONS

TEXT FIGURES

Appendix

PLATES INCLUDED IN TEXT

PLATES AT END OF TEXT

XXIV. - A. Hypidiomorphic texture of the non-opaque minerals.

B. Fine-grained aggregate of chondrodite enclosing apatite.

XXV. - A. Polysynthetic twinning in chondrodite.

B. Fine-grained aggregate of chondrodite crystals showing polysynthetic twinning.

XXVI. - A. Polygonal crystals of olivine in calcite matrix.

B. Selective core-alteration of chondrodite to serpentine.

XXVII. - A. Fibrolamellar structure of serpentine.

B. Interpenetrating polysynthetic twins of baddeleyite.

XXVIII. - A. Inclusions of phlogopite in magnetite.

B. Euhedral crystals of spinel included in magnetite.

XXIX. - A. Valleriite replacing magnetite and chalcopyrite.

B. Contemporaneous crystallization of magnetite and valleriite.

XXX. - A. Enlargement of centre of plate XXIX, fig. B.

B. Euhedral crystals of uranothorianite distributed throughout apatite and calcite gangue.

XXXI. - A. Euhedral crystals of uranothorianite in gangue.

B. Euhedral crystals of uranothorianite in magnetite.

XXXII. - A. Fragments of interstitial uranothorianite replacing calcite.

B. Pyrrhotite replacing calcite.

XXXIII. - A. Lamellar twinning in pyrrhotite.

B. Pentlandite in chalcopyrite.

XXXIV. - A. Ramifying veinlets of valleriite replacing magnetite.

B. Intergrowth of chalcopyrite and bornite showing mutual relations.

XXXV. - A. Cubanite residual associated with chalcopyrite.

B. Brecciated carbonate healed by chalcopyrite (polished section).

XXXVI. - A. Brecciated carbonate healed by chalcopyrite (thin section).

B. Ramifying veinlets of chalcopyrite replacing biotite and calcite.

XXXVII. - A. Chalcopyrite replacing calcite along cleavage traces.

XXXVII. - B. Bornite replacing gangue.

XXXVIII. - A. Grating texture of bornite developed in the crystallographic planes of chalcopyrite.

B. Bornite replacing chalcopyrite from a fracture.

XXXIX. - A. Replacement veins of chalcocite in magnetite.

B. Chalcocite vein etched with HNO_3 to reveal the parallel etch-cleavage of very fine-grained hypogene chalcocite.

LIST OF TABLES

APPENDIX

THE CARBONATE MEMBER OF THE PALABORA IGNEOUS COMPLEX

I. - INTRODUCTION

The alkali complexes can, broadly speaking, be separated into two classes. Firstly, those in which carbonate rocks form an integral part of the complex itself and secondly, where carbonate rocks, except perhaps carbonate country rocks, are absent. Both types are globally distributed; are generally characterised by distinct ring structures and become more basic inwards.

The Palabora Complex belongs to the first group. It has long stimulated the interest of both geologist and prospector but, except for small scale and unsuccessful attempts to exploit copper ores, the carbonate member was regarded as only of academic interest. The discovery in it of prescribed material[1] has, however, altered the picture.

It is of interest to review briefly the events which led to the discovery of the radioactive material present in the carbonate rock.

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1. For the purpose of the Atomic Energy Act, 1948, 'prescribed material' is defined as uranium, thorium, or any other material which the Governor-General may by proclamation declare to be prescribed.

During routine checks for radioactivity on rock samples in the Transvaal Museum a particular specimen was found to show considerable radioactivity but its locality could not be ascertained due to wrong labelling. It was suspected, however, that it may have come from Phalaborwa[2]. Subsequently, this area was included in a reconnaisance survey, undertaken by the writer during 1952, covering various mineralised areas in the Northern Transvaal in which radioactive minerals might be present.

The preliminary survey of the Palabora Complex showed that the surface material, covering the ground to the north-east of Loole Kop, was radioactive. Samples, taken from a dry water-course to the east of Loole Kop, were submitted tc the Geological Survey for identification. The mineral responsible for the activity was identified as uranothorianite, an oxide of thorium and uranium. The radioactivity was traced by radioactivity measurements to its source, which was found to be the centrally situated carbonate mass forming the elevated tract dominated by Loole Kop.

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2. There is a difference of opinion as to the spelling of the name of this locality. In the 'Official Place Names' recently compiled, it appears as Phalaborwa. The old spelling, Palabora, has long ago been accepted in geological literature and indexed as such. To change it now, can only lead to confusion. For this reason the old spelling has been retained as a collective term for the various geological formations and the new spelling is only used here in geographical sense.

Largely as the result of the possible strategic importance of the uranothorianite, a comprehensive prospecting programme was started during 1953. Resulting from this prospecting for uranothorianite it has been established that the deposit is actually a low grade copper deposit, with uranothorianite, magnetite and agricultural lime as by-products and it would appear to be of definite economic importance.

The difficulties experienced by numerous investigators to satisfactorily account for the field and geochemical relationships of the carbonate member to the other members of alkali complexes originally gave rise to two schools of thought. These are, the limestone assimilation and the metamorphic theories. Neither have, however, withstood the test of time and in recent years more and more support in favour of a magmatic origin for these carbonate rocks has been forthcoming.

The idea of a magmatic origin has been applied to a number of occurrences. The true nature of the carbonate members is still, however, not adequately solved, particularly, as in a large number of instances the possibility of assimilation and metamorphism of pre-existing calcareous country rocks by an invading magma cannot be ruled out. Many geologists remain unconvinced and regard the idea of an intrusive carbonate rock with frank scepticism.

The recent economic exploitation at Phalaborwa provides an opportunity to study the carbonate rock in detail a course which, particularly as the carbonate members of alkali complexes have in general been neglected in favour of the other members, may help to remove some of this scepticism.

The objects of this thesis are therefore;

1. To present new facts which have been collected as the result of an investigation of possible economic concentration of minerals in the carbonate member and,

2. to support, on the basis of this and other known information, a magmatic origin for it as the result of extreme differentiation at depth in which the sympathetic association of copper sulphides and uranothorianite marks the final stage.

A. Locality and Physical Features

The Palabora Igneous Complex forms part of the typical low-country bushveld of the North-eastern Transvaal. At Phalaborwa, however, the general monotony of the Lowveld is broken by closely spaced conical syenite and granite hills (plate II).

Plate II. - Conical syenite and granite hills, from Loole Kop beacon looking south-west.

The complex is situated close to the Kruger National Park and near the confluence of the Selati and Olifants rivers at latitude 23° 58' south and longitude 31° 8' east. In places it is covered by bush. The average elevation above sea-level is approximately 1200 feet. The highest ground is on top of the round hill, Loole Kop (plate I), approximately in the centre of the complex. The elevation at Loole Kop beacon is 1569 feet.

Although water was scarce in the past an adequate supply pumped from the perennial Olifants river some 7 miles south of the complex, is now available. Actual pumping is undertaken by the Phosphate Development Corporation and made available to other consumers at Phalaborwa.

While Phalaborwa enjoys a mild winter climate the summer months are unpleasant; temperatures in excess of 38°C (100.4°F) are often recorded. Rainfall is sporadic and occurs mainly during the summer months. In the past the prevalence of malaria, mostly of the malignant type, has been of considerable hindrance to the development of the area. Modern methods of control have, however, reduced the incidence of malaria to almost nil.

B. Review of Previous Literature

Although the earliest reference to Phalaborwa is the map by Carl Mauch 1868 showing the copper deposits, the first account of the general geology of the area was that of Mellor (1906) who described the limestone of Loole Kop and the associated igneous rocks.

Mellor was of the opinion that the granites at Phalaborwa show a transition to the pyroxenite suggesting a possibility that the granite magma was modified in composition by the influence of the limestone.

During 1912 Hall made an important contribution in the form of his memoir 'The Geology of the Murchison Range', extracts from which were communicated to the Geological Society of South Africa in two papers in the same year. Hall, concluded that, 'the complex is made up of a genetically connected series of massive granites, syenites and pyroxenites, which grade into one another and constitute a petrographical province, the members of which are derived from a common magma by progressive differentiation'. He suggested that, 'the normal syenites and pyroxenites are the later products of differentiation of a single magma, from which one partial magma split off and consolidated as pyroxenite, while a second less basic one carried most of the orthoclase components and gave rise to the syenite phase'.

In 1931 Shand published an account of the petrology of the various rock types. Shand developed Mellor's suggestion of desilication by limestone and regarded the pyroxenite as a product of gravitative differentiation. Desilication by limestone of an original granitic magma gave rise to a syenite magma from which diopside crystals settled out to form the pyroxenite. In the same year du Toit discussed the occurrence of apatite and suggested a metamorphic origin for the pyroxenite assemblage. A view which differs somewhat from that of Shand was proposed by du Toit who envisaged an acid magma acting upon a mass of siliceous dolomitic limestone, practically <u>in situ</u>, thus forming the pyroxenite.

C.M. Schwellnus published a brief account of the vermiculite deposits and drew attention to the archeological features of the area during 1938.

The results of a detailed investigation of the vermiculite deposits were given by Gevers in 1948, in which publication the general geology and petrology of the various rock types are discussed at some length. Gevers, supported the metamorphic origin suggested by du Toit as the most probable explanation of the origin of the pyroxenite.

In 1948 Brandt, in his unpublished dissertation entitled 'Die Geologie van 'n gebied in Noord-Oos Transvaal', suggested a deepseated magmatic origin for the carbonate rock by differentiation of a basic peridotitic-pyroxenite magma.

During 1954, Russell with Hiemstra and Groeneveld published a description on the mineralogy and petrology of the carbonate member of the complex.

This was followed, in 1955, by Hiemstra's paper on the mineralogy of baddeleyite from Phalaborwa.

II. - GENERAL GEOLOGY OF THE COMPLEX

It is not intended to give a detailed description of the geology of the complex. The general geology and petrography of the various rock types have been described in detail by Hall, Shand, du Toit and Brandt. The carbonate member, the host rock of the uranothorianite has, however, a particular bearing on the subject under consideration and will be dealt with fully.

The Palabora Complex, in which the carbonate rock occurs, covers an area of approximately 4 miles north-south and 2 miles east-west, and is set in granite. By far the greater portion of the complex is obscured by a cover of calcrete of varying thickness.

The distribution of the essential rock types to be found in the area is shown on the accompanying geological map (fig. 1), compiled by H.D. Russell, late of the Geological Survey, who remapped the complex during 1952. Subsequent mapping showed that the carbonate member occupied a smaller areal distribution than that originally shown by Russell.

The central portion of the complex consists of a roughly circular core of carbonate rock elongated in a east-west direction and separated from the surrounding granite by nearly concentric zones of desilicated rocks. These are, from the centre outwards, as follows:-

a. Carbonate

This is a fairly pure coarse- and medium-grained

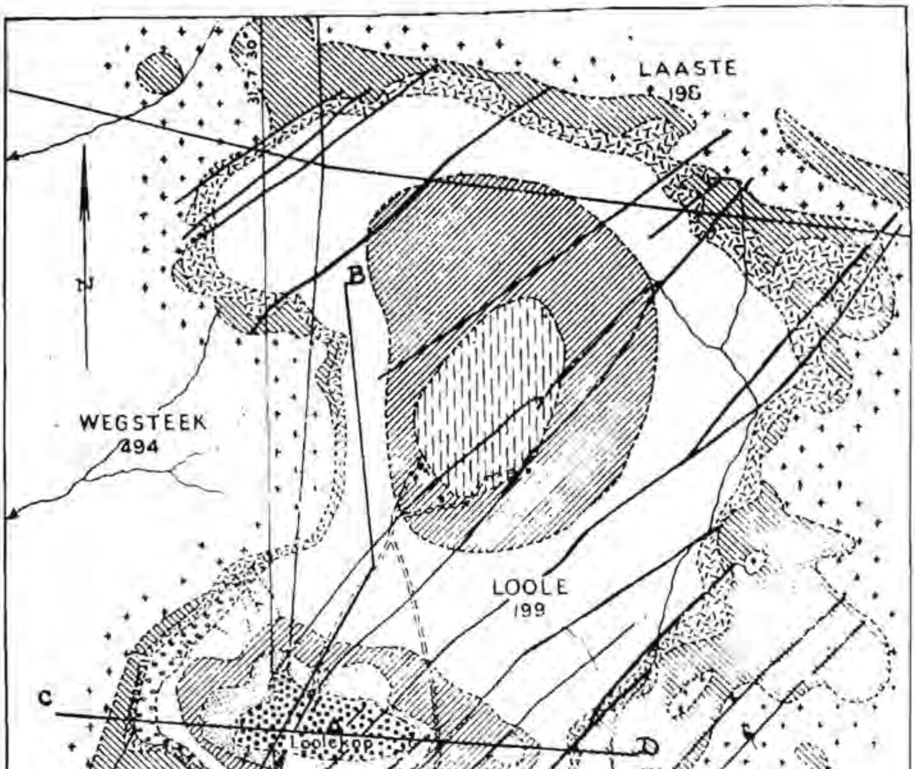


FIG. 1. Geological Map of the Palabora Complex.

(From Trans. Geol. Soc. S. Afr. LVII (1954), p. 198
Russell, Hiemstra and Groeneveld)

crystalline rock composed of magnesium-bearing calcium carbonate with scattered lumps and crystals of magnetite and apatite crystals. In it there are also subordinate amounts of copper sulphides and a number of rare minerals. The contact between the carbonate member and the magnetite-olivine-apatite rock which surrounds it is sharp and near vertical. The former often contains inclusions of the latter.

Thin veins of carbonate cut the other members of the complex. They contain chalcocite and chalcopyrite together with their alteration products.

b. Phoscorite

A magnetite-olivine-apatite zone, approximately 400 feet in width, occurs next to the carbonate member. The name 'phoscorite' has been given by Russell (1954), to this zone. This term is, however, accepted with reserve as being likely to lead to confusion with similar terms such as 'phosphorite'. It would perhaps be more appropriate to refer to this zone simply as the 'Apatite zone'.

At surface this body consists of a coarse-grained rock which macroscopically gives the impression that it is a breccia. The three main constituents are magnetite, serpentine and apatite. These vary in proportion from place to place and may be present in masses more than a foot in diameter. The apatite does not form separate crystals but, generally, occurs as coarse blebs and large masses. The phoscorite contains numerous pockets and bands of vermiculite, but the total amount is not considerable. Magnesian limestone is practically absent. In general the phoscorite is veined with magnetite and secondary carbonate.

The serpentine weathers to a hard dense limonitic material which together with greyish-green apatite and black magnetite impart to the rock a brown spotted appearance. Locally, the name 'spotted ore' is applied to this zone. Secondary copper minerals, mainly malachite, azurite, chrysocolla, and covellite are seen at surface. When fresh, the phoscorite is dark almost black in colour.

A second circular outcrop of phoscorite occurs approximately 1000 yards to the east of Loole beacon. No carbonate rock was found associated with this outcrop.

The contact between the phoscorite and the surrounding pegmatitic rocks is sharp. Inclusions of pyroxenite occur in the phoscorite. It is characterised by a massive vertical mineral banding.

c. Pegmatitic zone

This zone consists of pegmatitic rocks rich in vermiculite, diopside-pyroxene and serpentine. A gradational contact exists between this zone and the adjacent pyroxenite.

These pegmatitic rocks are developed at two main localities, the one surrounding the phoscorite zone in the environs of Loole Kop and the other some 2000 yards to the north. The northern occurrence has a younger pegmatoid core which shows a decrease of diopside towards the centre and consists predominantly of serpentinised olivine and vermiculite (Russell, 1954).

The main vermiculite production from the complex is derived from this pegmatoid core.

A third minor occurrence of pegmatitic rocks is developed to the south-east of Loole Kop, but here the pegmatoid is absent.

d. Pyroxenite

The pyroxenite is a massive medium green to dark green rock composed predominantly of diopside-pyroxene. Vermiculite and apatite are disseminated through it, but the distribution is variable and sporadic. To the west of Loole Kop the pyroxenite grades imperceptibly into glimmerite, a hydrobiotite-rich pyroxenite.

The pyroxenite forms by far the greater portion of the complex but its exact areal distribution is uncertain owing to the extensive cover of calcrete. Examination of the numerous prospect pits suggests that in general where calcrete occurs the underlying formation is usually pyroxenite, but this is not invariably the case.

e. Zone of shonkinite

This zone - pyroxenite with potash felspar- demarcates the pyroxenite from the granite and syenite. The impression gained is that this is a zone of assimilation. The contact with syenite is usually gradational but is sometimes sharp (Russell, 1954). The contact between the pyroxenite - shonkinite inner line is nowhere exposed but observations in numerous prospecting pits and trenches suggest that it is gradational (Brandt, 1948). The shonkinite appears to be felspathised-pyroxenite.

f. Syenite and granite

The above suite of rocks is completely surrounded by syenite and granite. South of Loole Kop syenite and granite extend for a considerable distance into the younger rocks of the complex.

The granite is Archaean and thus is part of the Basement complex. It is a highly leucocratic rock with only a small percentage of biotite. Normally pale pink to reddish, marginal facies show a green streakiness due to pyroxene. In general even-grained, the granite often becomes phorphyritic and large felspar phenocrysts are common, particularly near the contact.

The granite and syenite are intricately mixed especially near the contact with the pyroxenite, and are difficult to distinguish with certainty in the field. Along the north-eastern part of the complex the granite-syenite contact is near-vertical with a tendency to dip south-west. In this area the contact is often brecciated. On the west and south-west sides the contact is not sharp and the rocks in the contact zone are more often syenite pegmatites (Brandt, 1948).

The typical syenite, which gives rise to some of the 'tor-shaped' hills surrounding the complex, (plate II) is a coarse even-grained rock composed largely of potassium-rich microcline with subordinate amounts of pyroxene and amphibole.

g. Dolerite dykes

A large number of near-vertical dolerite dykes, trending in a NE-SW direction, cut the complex. The dyke contacts with the carbonate rock are sharply defined (plate III).

Plate III. - Dolerite dyke with apophysis (black) cutting carbonate rock.

In hand-specimen the dolerite is dark grey, medium- to fine-grained, and typical of Karroo dolerites. At the margin of the intrusions the texture becomes extremely fine-grained. Inclusions of carbonate rock are occasionally observed near the contact. Copper sulphides are sometimes concentrated in the dyke edges.

In thin section the material is seen to be composed of phenocrysts of labradorite set in a fine-grained matrix.

Legend

In order to avoid repetition of geological and other legends the following legend (fig. 2), common to all illustrations, is given.

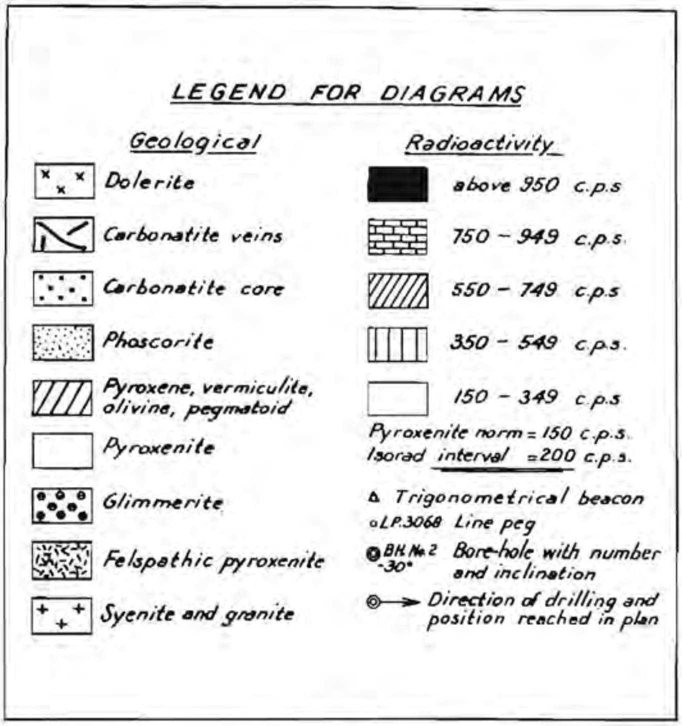


Fig. 2

III. - RADIOACTIVITY

A. Reconnaissance Survey

A reconnaissance radioactivity survey of the complex was made with a Ratemeter type 1011.B (plate IV), and a Halross scintillometer model 939 (plate V).

Plate IV. - RATEMETER, type 1011.B.
a. the ratemeter unit; b. the beta-probe unit and c. the gamma-probe unit.

At the time of undertaking this survey, the occurrence of radioactive material in the carbonate was not known. The object of the survey was, therefore, to test the possibility that the incorrectly labelled museum specimen originated from the Palabora Igneous Complex.

Furthermore, radioactivity surveys with sensitive instruments, such as the scintillometer, have been of assistance in geological investigations where the geology was largely obscured by surface cover derived from the underlying rock. If varying radioactivity normals between the different rock types which form the Complex could be established this would be of considerable assistance in elucidating the order of emplacement.

Plate V. - Halross model 939 SCINTILLOMETER.

a. ratemeter unit; b. probe unit containing photomultiplier and crystal. The probe is housed at the base of the ratemeter unit.

For the survey about 1200 radioactivity stations served to cover the complex. The stations were spaced approximately 200 feet apart. The position of each was accurately located on a base map.

Before dealing with the results of the reconnaissance survey several basic points must be considered:

1. Both instruments respond to cosmic and gamma radiations emanating from a radioactive source within their effective range. The response to cosmic rays can be satisfactorily determined for purposes of field-work by noting the lowest consistent count while traversing a formation of low activity. This reading is known as the 'background'. The true reading is then the difference between the background and the observed count.

The background count was obtained by traverses over the pyroxenite. Backgrounds of 13 and 150 counts per minute were obtained for the ratemeter and scintillometer respectively. Since a drift of the scintillometer-calibration was observed with variations in plateau voltage, constant reference to base stations, selected on pyroxenite, was necessary.

2. The reading obtained from a source of radioactivity is dependent on three basic factors:

a. The angle formed between the instrument at the apex and the boundaries of the surface of the radioactive source. In other words, the response to any particular source will be greatest in mine workings where the solid angle reaches a maximum. For the same source the response will reach a minimum when dealing with a level plane i.e. instrument response to the solid angle decreases with the square of the distance. In practice all conditions falling within these extremes are met with. Field results are therefore regarded as qualitative rather than quantitative.

b. Absorption of gamma radiations by air limits the effective range of the instruments, but can be disregarded for field surveys. For consistency, readings were taken at a fixed height above ground-level. For ease of operation this is normally at waist-height. It is not desirable to take readings with the instruments placed on the ground. This magnifies discrepancies from a point source and reduces the radioactivity cover obtained.

c. Absorption of radiation by a dense medium such as rock is an important consideration. Errington (1950) states that 2 to 3 inches of rock will reduce the signal strength by a factor of two and a layer 2 feet thick will reduce it by a factor of 1000. The results from a radiometric field survey, therefore, represent only radiations from the surface skin. Fortunately, the radioactive content of the overlying soil is generally indicative of the underlying rock formation if due allowance is made for soil-movement.

The results of the reconnaissance survey were studied by constructing an <u>isorad</u>[1] map. Because of the wide spacing of traverses and the influence of radioactive surface material, only generalised conclusions

---

1. Isorad lines may be defined as lines of equal radioactivity intensity.

could be drawn. For this reason, the isorad map based on the results from the reconnaissance survey is not included. By plotting radioactivity traverses against the relative diagrammatic geological sections a better idea of the distribution of radioactive material was obtained. Two of these traverses are shown in figure 3. The approximate traverse lines along which the geological sections were drawn are shown in figure 1.

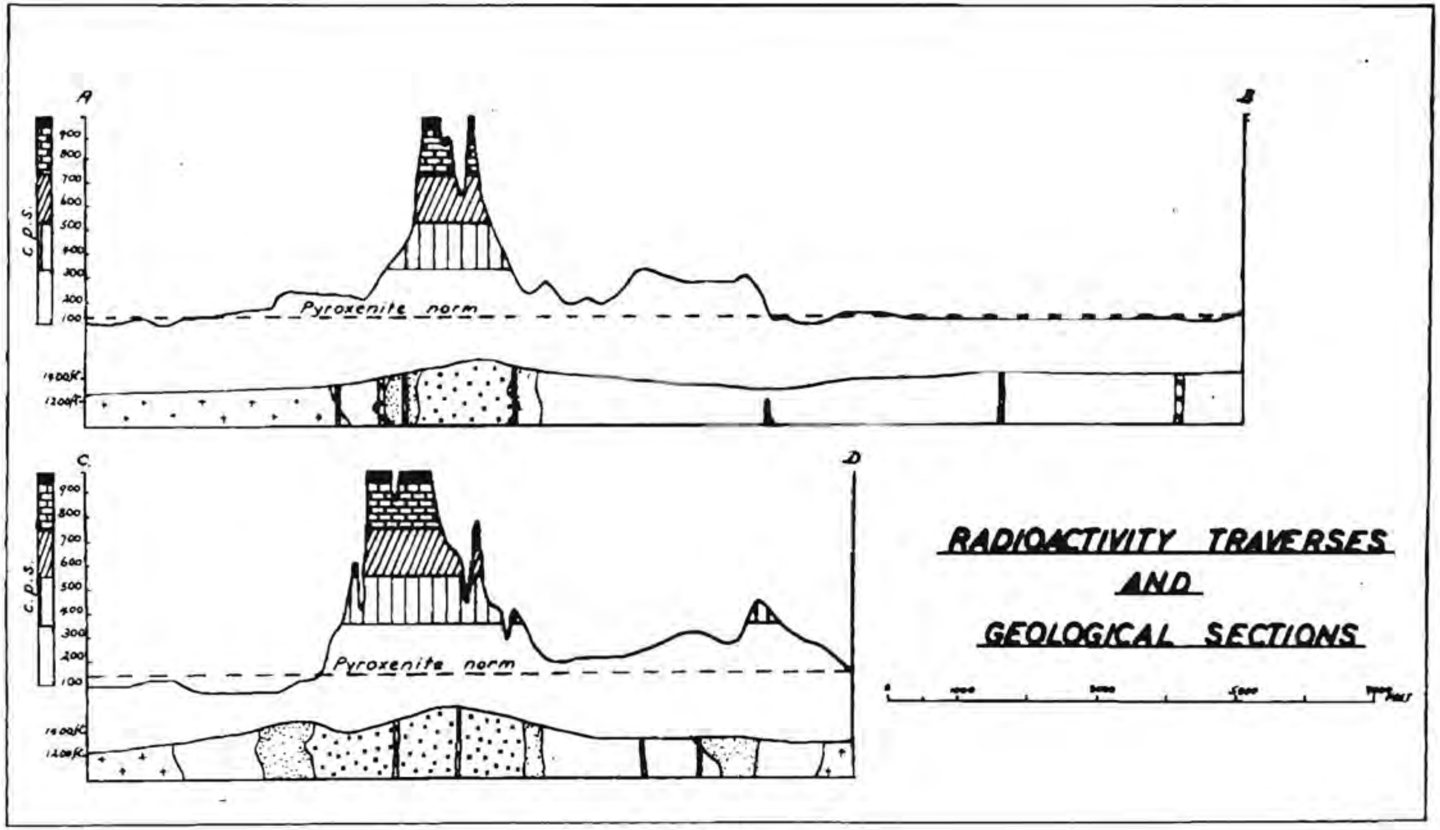
The following conclusions can be drawn from the reconnaissance survey:-

1. Despite the increased sensitivity of the scintillometer the survey failed to assist in tracing concealed contacts. The instruments could not distinguish between the pyroxenite and syenite of the complex and the surrounding granite, nor could any differences of radioactive norm be established between the granite and syenite.

2. The radioactivity was traced to the carbonate member. While no zones of mineralization could be distinguished, areas of relatively low activity observed on the carbonate member suggested that radioactive material was irregularly distributed.

3. The highest readings were obtained in the vicinity of Loole Kop beacon. Scintillometer readings were often as high as 2500 counts per second or 2350 above pyroxenite norm. Readings dropped abruptly when on formations other than the carbonate. Anomalous readings were obtained to the east of the Loole Kop beacon. Investigation proved these anomalies to be due to surface radioactive material, rich in magnetite.

4. The agreement between results obtained by the two instruments was good. On an average a ratio of 1:10



A
B
C
D
c.p.s.
100
200
300
400
500
600
700
800
900
Pyroxenite norm
1400ft
1200ft
RADIOACTIVITY TRAVERSES
AND
GEOLOGICAL SECTIONS
0
1000
3000
5000
7000
FEET

FIG. 3.

was obtained. There was, however, some considerable variation from the average and extremes in ratio of 1:4 to 1:27 were found. The largest variation from the average was obtained at points of low radioactivity. From these observations it is apparent that the particular scintillometer used had a sensitivity only 10 times greater than the ratemeter.

B. Detailed Survey of Loole Kop and Surroundings

Once the radioactivity associated with the carbonate member was recognised it became obvious that a detailed survey of Loole Kop and surrounding area was necessary, to define the extent of the radioactivity at surface and detect any possible mineralised zones. It was also necessary to establish if any radioactive material was associated with the veins of carbonate.

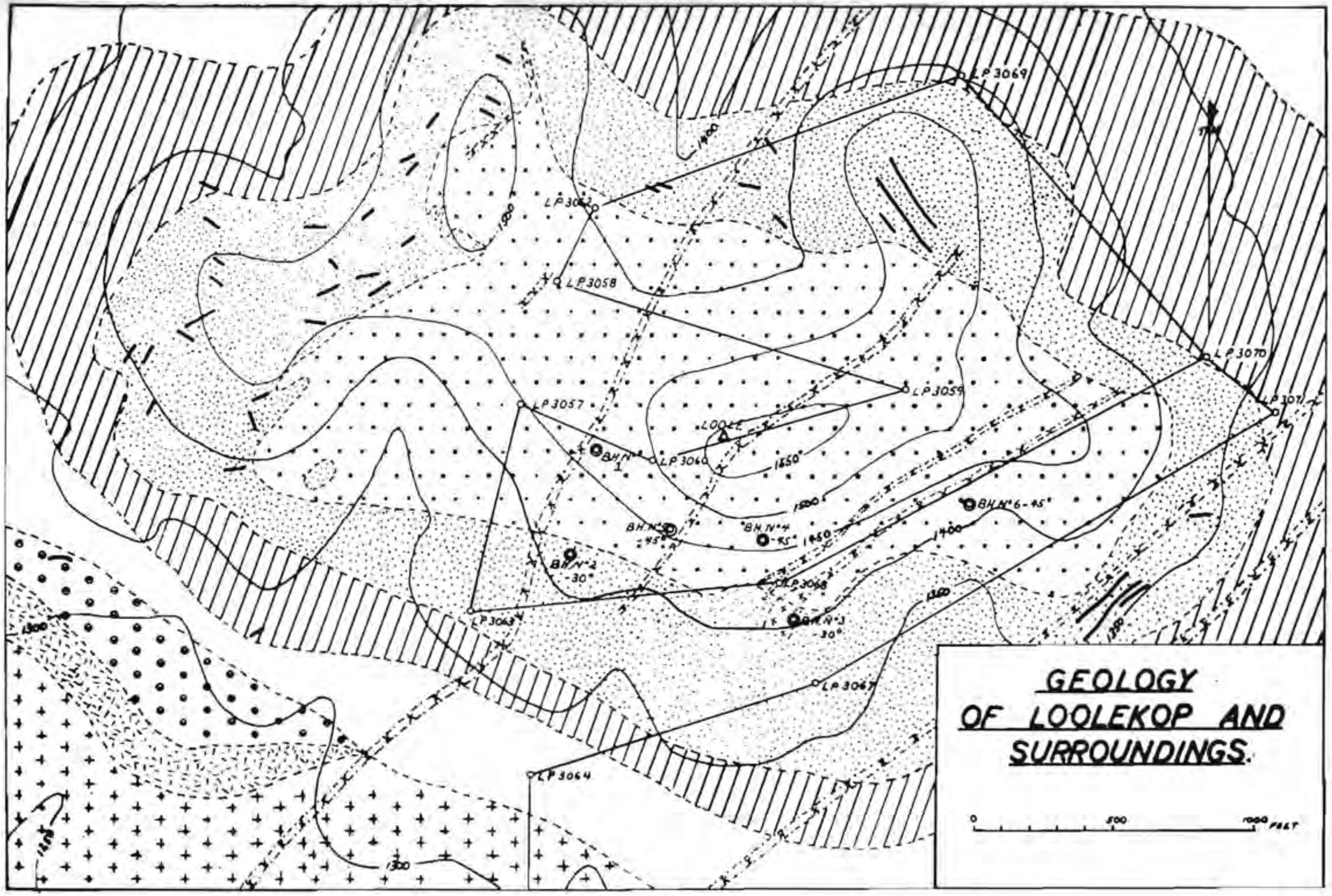
The survey was confined to the area covered by figure 4 and was done by running closely spaced traverse lines across it. Control was maintained by a tie-up of traverse lines to the line-peg beacons. At each primary station falling on a traverse line, a fan of secondary stations were set out. The average spacing between stations was approximately 25 feet. Owing to the abundant magnetite lying on the surface a compass could not be used and the setting out of stations was done with a Wild Tachyometer. This method gave adequate cover for radioactivity mapping.

The isorad map (fig. 5) confirmed the preliminary results in that, apart from surface contamination as the result of weathering and subsequent transportation, the radioactivity is concentrated in irregular zones in the carbonate member. Although the zones of greater activity show an irregular distribution at surface, the elongation of the group in a N.W.-S.E. direction suggest that they may form a continous zone at depth below the soil-mantle.

No radioactivity was found associated with the veins of carbonate rock visited. This does not, however, rule out the possibility that veins with which radioactive material is associated do occur.

In evaluating the surface distribution of radioactive material, as shown by the isorad map, soil-movement is a significant factor. The influence of topography can be seen from the sympathetic relation between isorad and contour lines. The probable direction of movement of radioactive material, set free by weathering, is indicated on the isorad map. It can be seen that isorad lines extend in sympathy with the drainage-pattern. The main direction of movement is to the south of the watershed formed by the high ground of Loole Kop, in which direction exaggerated radioactive anomalies can be expected.

The surveys indicate that the bulk of radioactive surface material occurs covering the lowlying ground south of Loole Kop and over a relatively large area of pyroxenite to the east.


GEOLOGY
OF LOOLEKOP AND
SURROUNDINGS.
0
500
1000 FEET
L.P. 3069
L.P. 3070
L.P. 3071
L.P. 3059
L.P. 3058
L.P. 3057
L.P. 3060
L.P. 3063
L.P. 3064
L.P. 3067
L.P. 3068
LOOLEKOP
B.H. Nº 1
B.H. Nº 2 -30°
B.H. Nº 3 -30°
B.H. Nº 4 -45°
B.H. Nº 5 -45°
B.H. Nº 6 -45°
1300
1350
1400
1450
1500
1550

F I G. 4.

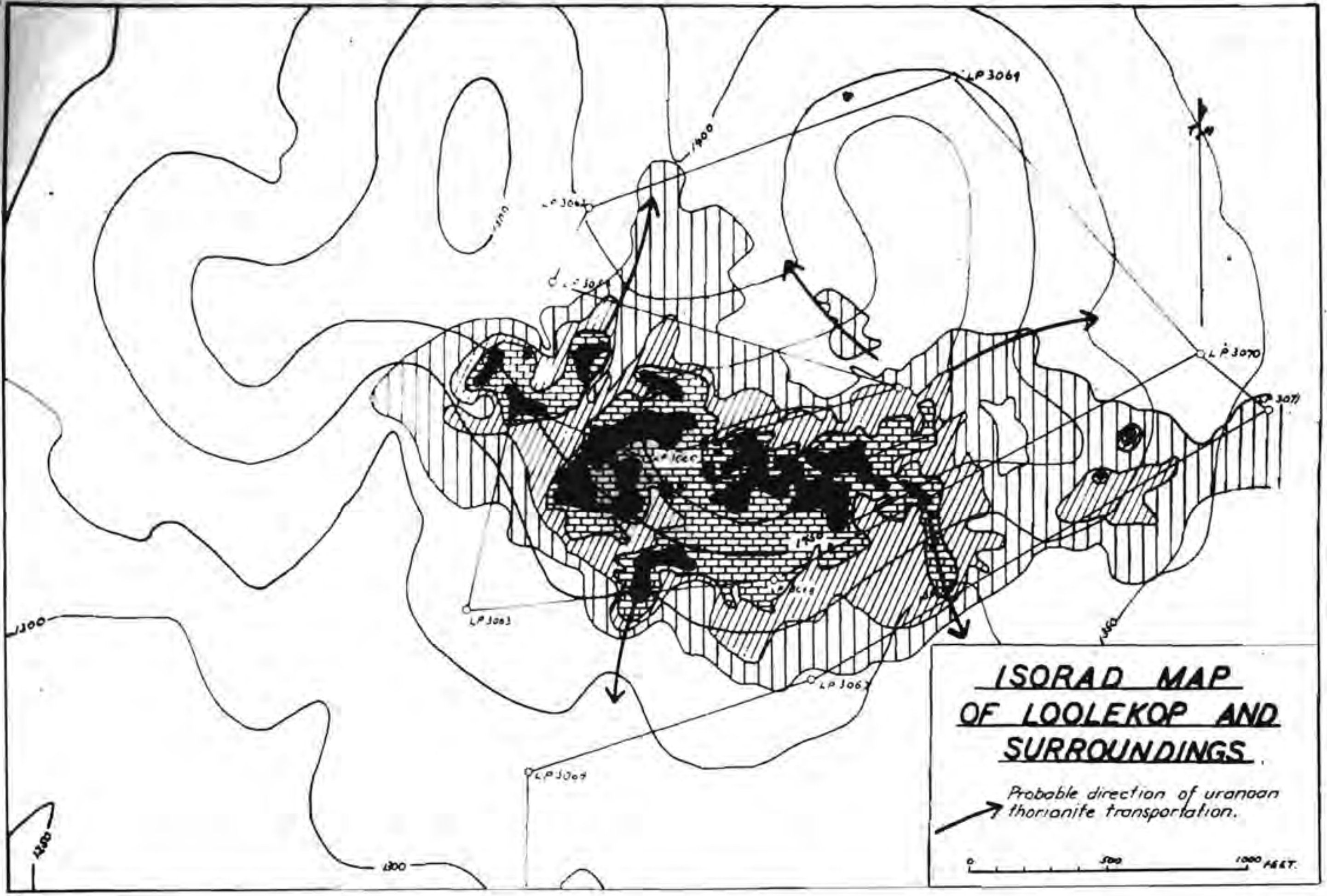

ISORAD MAP
OF LOOLEKOP AND
SURROUNDINGS.
Probable direction of uranoan thorianite transportation.
0
500
1000 FEET.
L.P. 3069
L.P. 3070
L.P. 3063
L.P. 3062
L.P. 3067
1400
1300
1200

FIG. 5.

IV. - THE CARBONATE MEMBER

A. Petrology

The carbonate core covers an area of approximately 1000 by 400 yards and is elongated in an east-west direction (fig. 4). It consists of both coarse and medium-grained crystalline calcium-magnesian carbonate, usually white in colour, but occasionally varying to a dirty yellow.

Macroscopically magnetite, apatite, mica and subordinate amounts of malachite, azurite, chrysocolla and covellite can be recognised at surface.

The carbonate mass is not characterised by a zone of oxidation which, in copper deposits, is generally observed down to the water-table. Drilling shows that there is no water-table as such and that the depth of oxidation is normally less than 10 feet. Oxidation associated with jointing is, however, developed to greater depths.

Mineral banding, particularly noticeable in the case of magnetite, is quite distinct and at surface suggests an apparent parallel arrangement with respect to the elongation of the core. The bands of magnetite, where emphasised by the removal of carbonates by weathering, appear to be standing at very high angles and give the impression of being vertical or near-vertical (pl. VI, figs. A and B).

Fig. A. Vertically disposed carbonate outcrop elongated in an east-west direction. Relief is the result of weathering.
Scale object = 1 ft.

Fig. B. Carbonate outcrop showing the vertical disposition of the magnetite bands at surface.
Scale : 1" = ft.

Plate VI

Owing to the extensive scree cover the contact between the phoscorite and the carbonate member is nowhere well exposed. Prospecting and drilling, however, show the contact to be sharp and near-vertical (pl. VII). Inclusions of phoscorite in the carbonate are common near the contact.

Plate VII. - Photograph of a polished specimen of core from bore-hole 8, drilled at 60 degrees from vertical, showing the contact of the carbonate member (white) with phoscorite (mottled).

Thin carbonate veins cut the phoscorite, pyroxene-vermiculite-olivine pegmatoid and adjacent pyroxenite. The distribution of these veins, as observed in prospecting pits and trenches, is shown on the geological map (fig. 4). These veins are prominent in the phoscorite and have a radial distribution around the western flanks of Loole Kop. Because of the nature of the ground the veins shown are probably only a portion of those which have intruded the complex. Their dip is usually steep. They are indentical to the carbonate core. They carry essentially the same mineral assemblage, predominantly magnetite, apatite and serpentine. In places they show copper staining and, very occasionally, small specks of copper sulphides.

Underground, a better conception of the nature and distribution of the various minerals within the carbonate member is obtained. It is seen to be mineralogically complex and consists of crystalline magnesian limestone normally pure white. Predominantly coarse to medium-grained it passes locally into finer-grained types. Scattered in it are apatite, chondrodite, olivine, phlogopite, and biotite. Serpentine is of frequent occurrence. The ore minerals which can be macroscopically recognised are magnetite and copper sulphides. A bronze tarnish caused by valleriite can often be observed on fresh magnetite surfaces.

The ore minerals, ferromagnesian silicates and apatite occur as coarse-grained aggregates often several feet across, and vertical bands varying from a fraction of an inch to several feet in width.

These vertical bands are well exposed in the south adit driven in a northernly direction from the southern slopes of Loole Kop (fig. 17). The minerals and mineral streaks are arranged along roughly parallel lines and are suggestive of linear parallelism (pl. VIII, fig. A and B). Drives, east and west, do not show this structure clearly.

The bands are generally monomineralic and are usually composed of magnetite which, in the more robust cases, are seen to be formed of a series of irregular fragments aligned vertically. The softer sulphides form less robust bands which consist of aligned streaks and irregular blebs of sulphides in carbonate (pl. IX, fig. A and B, pl. X, fig. A). Occasionally the gangue minerals show a rude banding due to the vertical alignment of isolated lumps. The bands are not continuous and tend to pinch out over varying distances. Often a well developed band on one adit face cannot be detected on the opposite face.

The change from banded structure to coarse-grained aggregates is abrupt (pl. VIII, fig. B). The aggregates and zones of vertical bands pass into areas of almost pure magnesian calcium carbonate.

No evidence of metamorphism of the carbonate member at its contact with the phoscorite exists and mineralization is poor at the contact. No decrease in the coarseness of the crystalline texture of the carbonate is to be seen towards the centre. There is, however, a marked change in the carbonate as a whole as it becomes noticeably pegmatitic. In this pegmatitic phase, developed in the central portion of the body, minerals that are easily recognised occur in relatively large lumps and brecciation is common. Macroscopically copper sulphides and serpentine can be seen to recement the fragments.

The carbonate member is generally massive but has joints and fractures suggestive of tension joints probably due to cooling and crystallization of the mass. Slickensided surfaces suggest many of the joints to be slip planes (pl. XI, fig. A and B). They reach their maximum development towards the centre of the body.

The attitude of the joints was studied by constructing a point diagram using an equal area projection and plotting on the upper hemisphere (Haff, 1938; Billings, 1942). From the point diagram a contour diagram (fig. 5A) was constructed. The contour diagram shows that of the 162 joints measured the majority strike north-east while they all dip steeply.

Although many of the joints are developed on original bands of copper mineralization, which evidently acted as planes of weakness, some of the mineralization suggests enrichment of copper sulphides along earlier formed joint planes. Copper sulphides are also seen to cause enrichment in adjacent carbonate rock by development from these joint planes. Furthermore, veins of copper sulphides are occasionally seen to bend away when obstructed by aggregates of ferromagnesian silicates.

Where joints have opened secondary calcite has filled the openings (pl. X, fig. B). Further opening of these joints has allowed the growth of a second crop of calcite crystals. Secondary pyrite crystals are intergrown with the calcite in these joints (pl. XIV).

A noticeable increase in radioactivity occurs, and copper mineralization is improved over the section where the maximum development of jointing and brecciation is observed.

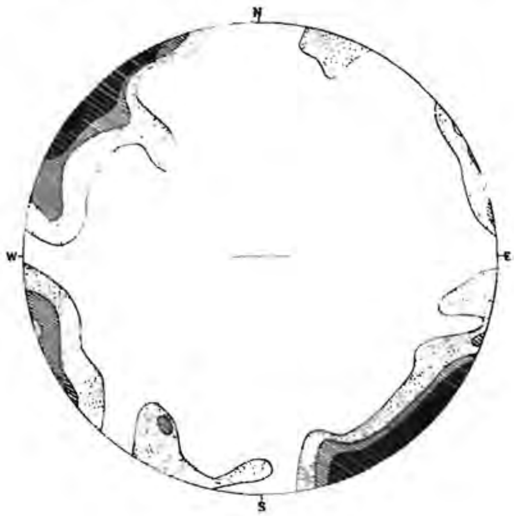
In order to establish if there is any connection between the main trends of jointing now observed and bands of copper mineralization a contour diagram was constructed of 151 bands in the same way as for the joints. The diagram (fig. 5A) shows that while there is a wide variation in strike, four directions predominate. Of these the majority strike N 8 E and N 28 W, while two minor sets strike N 33 E and N 63 W. Only those striking N 33 E follow the jointing. All the bands, however, dip steeply.

Near-vertical joints filled with serpentine are seen. The material in these joints shows rythmic layering parallel to the sides. Mineralogical examination showed the material to consist of a white fibrous variety of serpentine alternating with a pale green massive variety (pl. XII).

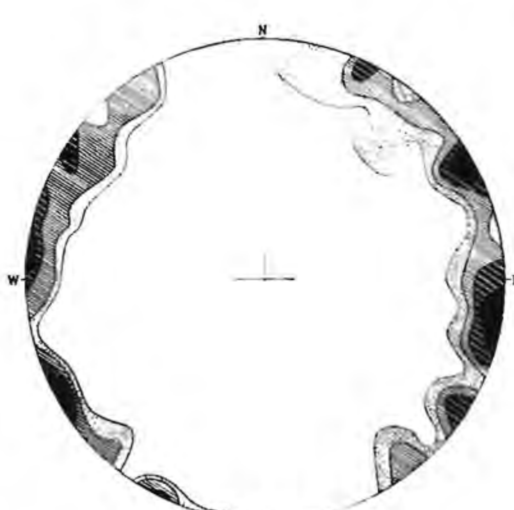
In the adit, at 416 feet from the entrance, there is a nearly vertical fault striking N 63° E. The fault-plane is filled with 1 to 2 inches of soft gouge. On the south side of the fault the carbonate is finer-grained whereas on the north side of it there is a zone of brecciation up to 2 feet wide that passes into a zone of intense jointing. The joints, irregular and closely spaced, in turn fade out gradually (pl. XIII, figs. A and B).

CONTOUR DIAGRAMS

162 JOINTS EXPOSED IN THE UNDERGROUND WORKINGS



151 BANDS OF COPPER MINERALIZATION EXPOSED IN THE UNDERGROUND WORKINGS



0-1% 1-3% 3-5% 5-7% 7-9%

Fig 5A

Plate VIII

Plate VIII

Fig. A. Parallel vertical bands of magnetite. The more prominent bands consist of fragments such as would be expected from pressure normal to the band.

Fig. B. Photograph illustrating the abrupt change from banded carbonate to a coarse-grained aggregate showing only very rude banding. A joint cuts the well-banded section without causing displacement. Chalcopyrite is concentrated in a zone cutting diagonally across the rudely-banded area to the right.

Fig. A.

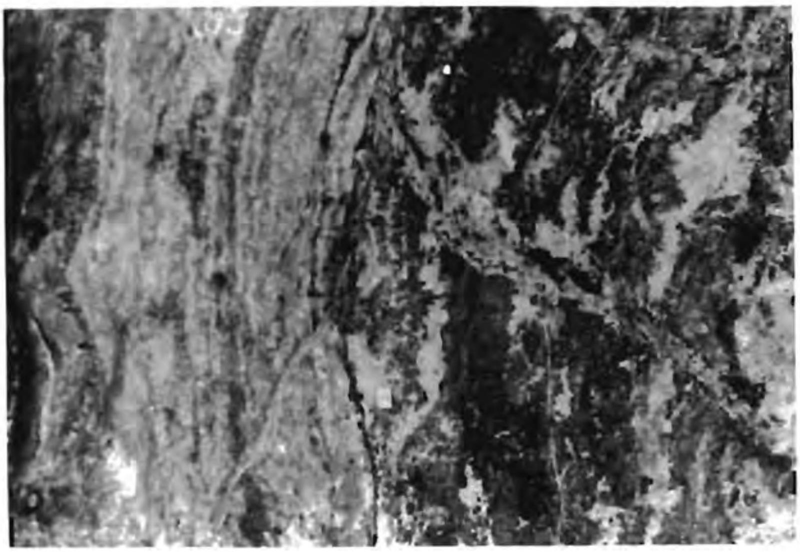


Fig. B.

Plate VIII.

Plate IX

Plate IX

Fig. A. Near-vertical streaks of chalcopyrite developed in rude bands of carbonate (white). Larger dark areas represent coarse mineral aggregates.

Fig. B. Small streaky masses of chalcopyrite (grey) showing a tendency towards vertical alignment. The larger black areas are magnetite in carbonate (white).

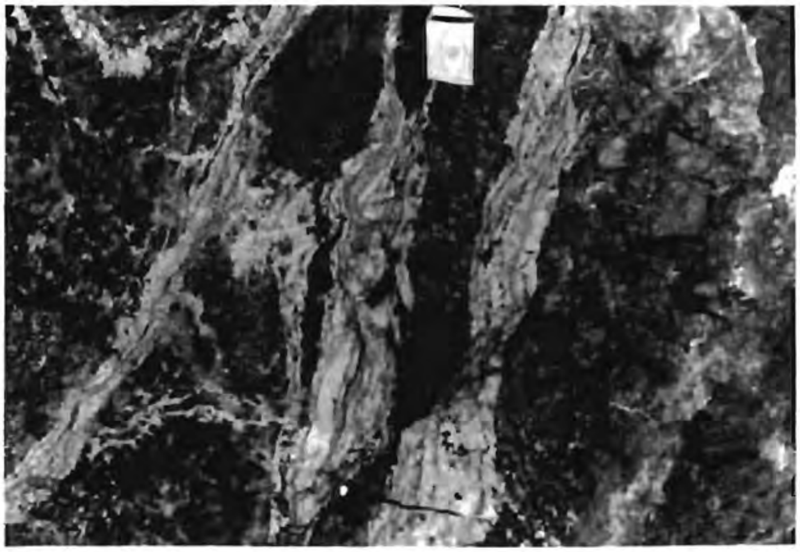


Fig. A.

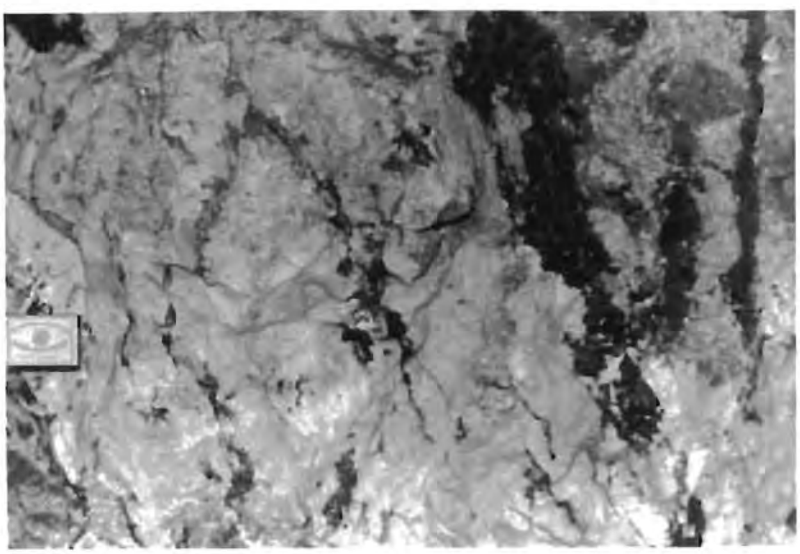


Fig. B.

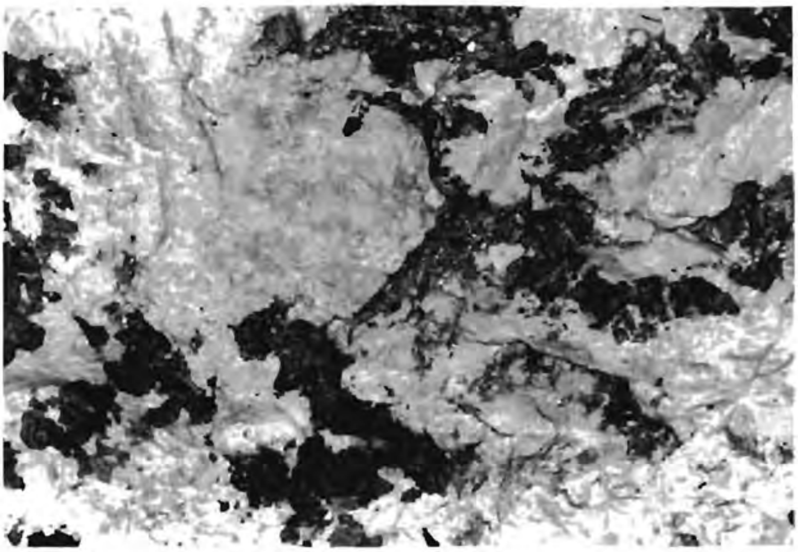
Plate IX.

Plate X

Plate X

Fig. A. Irregular distribution of chalcopyrite (dark grey) closely associated with magnetite (black) in carbonate (white).

Fig. B. Irregularly jointed carbonate, varying from nearly clean carbonate to coarse aggregates. Sulphides are associated with the joints from which the carbonate is enriched. A vertical open joint refilled with secondary calcite occurs at the extreme right.
Dark is magnetite; grey copper sulphides and gangue other than carbonate; white is carbonate and secondary calcite.



Scale: 1" = 1 ft.

Fig. A.

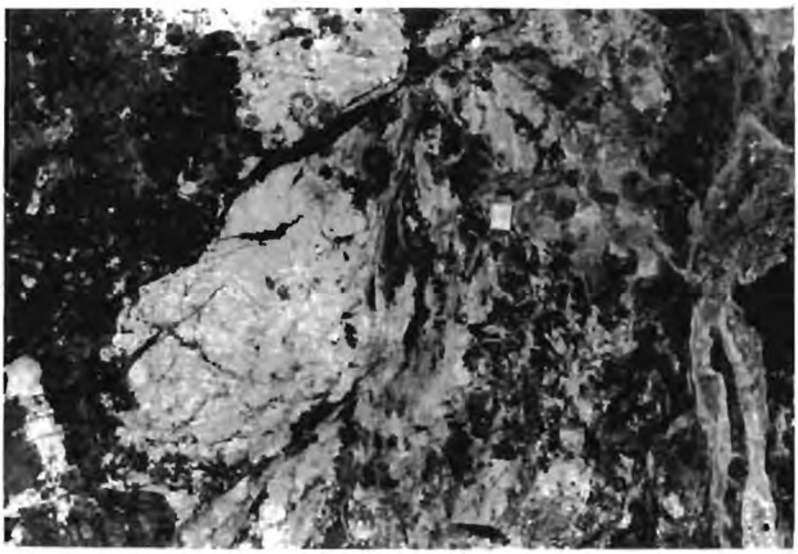


Fig. B.

Plate X

Plate XI

Plate XI

Fig. A. Copper sulphides (grey), concentrated along parallel near-vertically disposed joints. Magnetite (dark) is irregularly distributed throughout the carbonate (white). The grey area below the scale object is a shadow cast by a surface irregularity.

Fig. B. Parallel vertical slip-planes (dark) transgressing an extremely coarse aggregate of chalcopyrite (grey) magnetite (dark) and carbonate (white). The surfaces on which slickensiding can be observed, appear dark as they have been emphasized by the shadow obtained by taking the photograph at an oblique angle to the face.

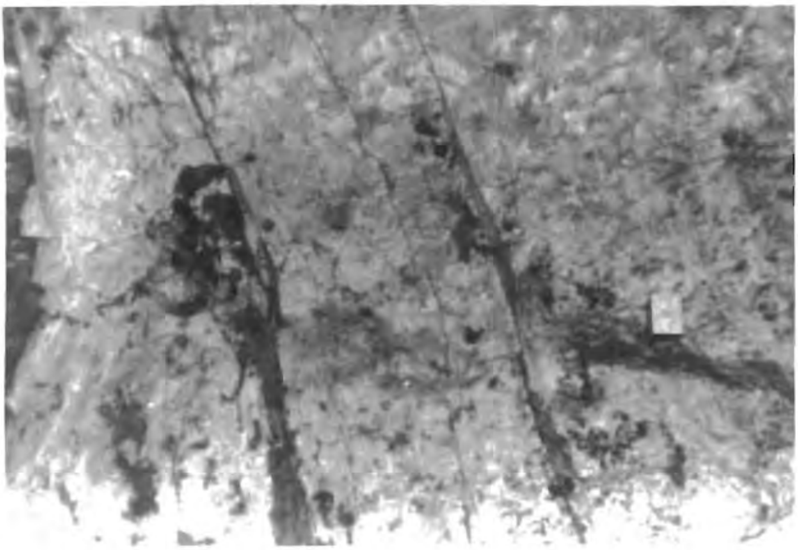


Fig. A.

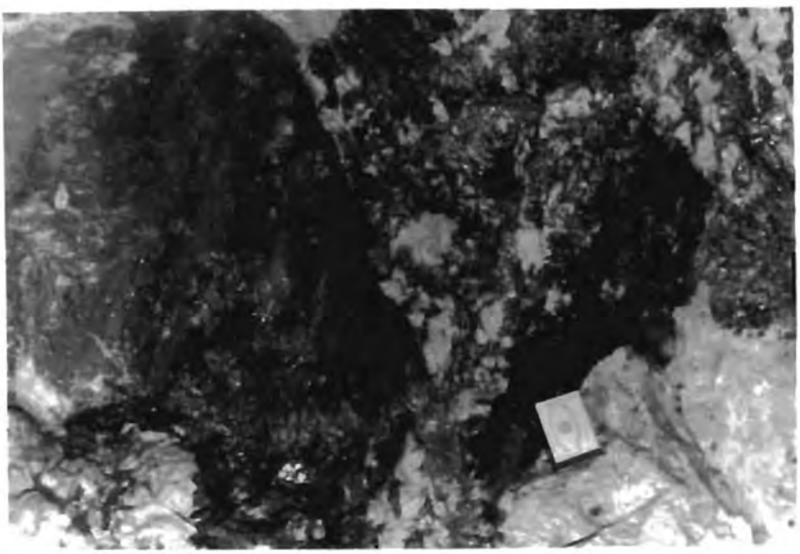


Fig. B.

Plate XI.

Plate XII. - Serpentine filling a vertical fracture in carbonate. Crustification can be seen particularly at the contacts. The dark bands are due to a greenish massive variety alternating with light bands of a white fibro-lamellar variety.

Plate XIII

Plate XIII

Fig. A. Gouge, visible as a narrow vertical dark stripe across the centre of the photograph, developed in a fault-plane. The carbonate (white) to the right of the fault is brecciated and recemented by chalcopyrite (grey). To the left, magnetite (dark) and thin vertical streaks of chalcopyrite occur in coarsely crystalline carbonate.

Fig. B. Photograph of a pair of branching fault-planes exposed in the hanging. The brecciation of the upper section is clearly seen. The lower section consists of carbonate in which mineralized veins develop from the fault. The white area to the upper left of the scale object is secondary calcite developed adjacent to the fault-plane.

Fig. A.

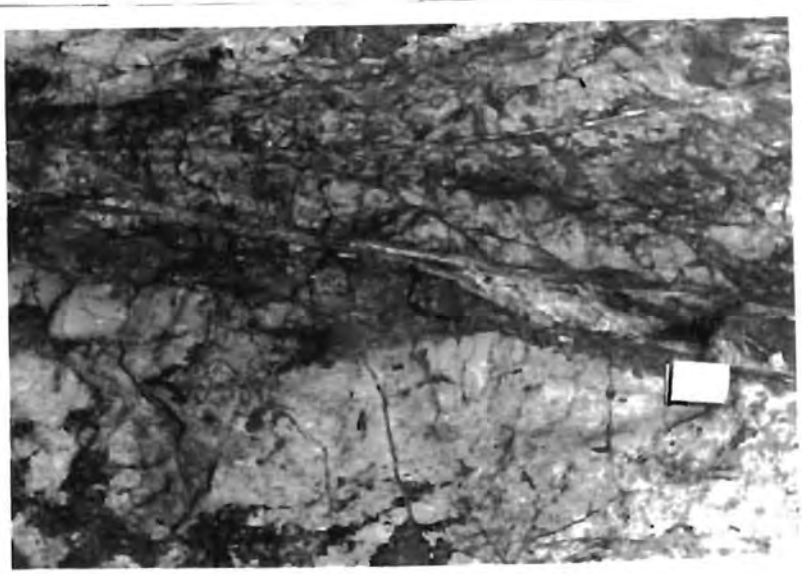


Fig. B.

Plate XIII.

B. Mineralogy

1. General

The distribution of the minerals which comprise the carbonate member is extremely variable. Extremes from barren carbonate to highly mineralised sections occur.

Information on the identification and textural relationships of the various minerals present was obtained by a study of thin and polished sections. In the case of the opaque minerals the procedure outlined by Short (1940) was followed. Etch reagents were allowed to remain in contact with specimens for a period of one minute.

Studying a rock type composed largely of magnesium-calcium carbonate along the lines suggested by Short presented a serious difficulty. Both nitric and hydrochloric acid react vigorously, in the cold, with the calcite thus obscuring etch reactions obtained on the ore minerals. In cases of doubtful etch reactions it was necessary to obtain confirmation by x-rays.

In thin section the carbonate member is seen to be, in general, coarse-grained and of a holocrystalline hypidiomorphic texture (pl. XXIV, fig. A). The non-opaque minerals and the oxides show a marked tendency to occur as crystals. The sulphides on the other-hand are massive. In general copper sulphides are macroscopically visible in the richer concentrations of the ore and can easily be identified in hand-specimen. The uranothorianite crystals are tiny and in hand-specimen cannot be distinguished from small specks of magnetite. In order to limit the number of specimens selected for polishing a geiger-counter was used to select samples rich in uranothorianite.

The following minerals listed in order of relative abundance have been recognised:

Non-opaque minerals.

Calcite and dolomite, chondrodite, olivine, apatite, phlogopite, biotite, baddeleyite, spinel and fluorite.

Opaque minerals.

Magnetite, chalcopyrite, bornite, chalcocite, valleriite, pyrrhotite, pentlandite, cubanite and uranothorianite.

In view of the brief and inadequate description of the mineralogy of the carbonate member given by Russell and others (1954) it is necessary to enlarge thereon. Their work concerns itself almost entirely with the question of identification and neglects the textural relationships. In addition it must be stated that the facts presented here were obtained independently by the writer. The mineralogical investigations having paralleled in time those of Russell.

For convenience of description the non-opaque and opaque minerals are dealt with under separate headings. The minerals are discussed in order of their probable paragenesis.

The optical properties of the non-opaque minerals have been determined by Russel and others (1954). The values given are those determined by them.

2. The Non-opaque Minerals

Under the microscope the dolomitic-calcite is seen to be completely crystalline with coarse anhedral crystals varying from less than 0.1 mm to as much as 2 centimetres.

On etching with nitric acid the crystals are resolved to show an intergrowth of calcite and dolomite. The dolomite crystals are raised in relief owing to their lower solubility. They occupy a seriate arrangement in the calcite (Russell 1954, pl. XXXI, fig. I). The intergrowth of calcite and dolomite suggests an origin by exsolution for the dolomite.

Alteration occurs as limonitic stains, replacement by copper oxides and green, slightly pleochroic, malachite. In the vicinity of dyke contacts it is generally turbid and stained. It is often brecciated and is then healed by copper sulphides (pl. XXXV, fig. B, pl. XXXVI, fig. A) or serpentine.

Secondary calcite is developed in veins and joints which transgress the carbonate member. This calcite shows growth layers due to successive deposition and crystallization of carbonate-saturated solutions. Pyrite occurring as well-developed, striated cubes, on an average 1 mm in size, is associated with it (pl. XIV).

The available chemical analyses of the carbonate member are given in table II.

Spectrographic analysis (Russell 1954) shows the M_gO content to vary from 3 to 8 per cent with a mean value of 4.8 per cent, about 2 per cent FeO, 0.4 per cent SrO, and 0.03 per cent BaO.

Russell (1954) on the basis of his and Higazy's (1954) work has suggested that the exsolution-textures of dolomite in calcite together with the high Sr and Ba content may be criteria for the formation of the carbonate member at high temperature and may possibly be diagnostic for carbonate rocks of volcanic origin.

The apatite is easily recognised in hand-specimen by its light greenish colour. Colourless in thin section it occurs as well-formed euhedral prismatic and tabular crystals. Crystals showing irregular outlines are less common while crystalline aggregates occur fairly frequently.

The crystals vary in size from less than 1 mm to large crystals of more than 4 centimetres in length. The larger crystals are often cracked and strained. The resulting fractures are filled with calcite and less often with magnetite. Occasionally the apatite has inclusions in it of calcite. Inclusions of it have been seen in calcite, chondrodite, magnetite, uranothorianite and spinel.

The crystal form suggests the apatite is an early formed constituent which shows strain possibly due to stresses set up during crystallization of the remainder

TABLE NO. I - EXPLANATION

1. Coarse white crystalline limestone with magnetite and apatite. Source: Wybergh, W. (1919).
2. As above, without apatite. Source: Wybergh, W (1918).
3. As above, with much apatite. Source: Wybergh, W. (1918).
4. Limestone pillar in ancient Lulukop workings. Anal. Dr. Moir. Source: Hall, A.L. (1912).
5. Limestone, Lulukop, Palabora. Anal. S.J. Shand. Source: S.J. Shand (1931).
6. Analysis of eleven samples of pure carbonate rock. Anal. Dr. J.C. Dunne. Source: Gevers (1948).
7. Partial analysis of representative portion of five underground sample of carbonate rock. Magnetite removed. Anal. A. Kruger. (Div. of Chemical Services). New analysis.

TABLE NO. I

CHEMICAL ANALYSES OF THE CARBONATE MEMBER

	1.	2.	3.	4.	5.	6.	7.
SiO_2	0.5	2.3	1.0	-	0.29	-	-
CaO	51.75	43.2	46.9	34.50	42.07	49.07	38.64
MgO	2.85	5.15	3.9	3.40	11.08	5.11	9.90
Fe_3O_4	0.4	8.15	5.7	-	-	-	-
Fe_2O_3	-	0.35	0.5	-	-	0.84	-
Fe in Fe CO_3	0.65	0.65	0.6	-	-	-	-
Al_2O_3	0.2	0.5	0.8	-	-	-	-
P_2O_5	0.45	3.15	3.2	1.00	0.19	-	-
SrO	-	-	-	2.70	0.43	-	0.63
$SrSO_4$	-	-	-	0.25	-	-	-
CO_2	-	-	-	-	45.25	43.90	42.12
$CO_2 + H_2O$ trace	42.9	36.3	37.1	-	-	-	-
F, K_2O, SO_3	0.1	0.25	0.3	-	-	-	-
Igni. CO_2	-	-	-	32.00	-	-	-
O - Diff	-	-	-	5.82	-	-	-
H_2O	-	-	-	0.31	-	1.20	-
Insol SiO_2	-	-	-	3.25	-	0.15	-
Fe	-	-	-	15.25	-	-	-
Cu	-	-	-	1.52	-	-	trace
(Fe Mn) O	-	-	-	-	0.93	-	-
MnO	-	-	-	-	-	0.09	-
Totals	99.8	100.0	100.0	100.0	100.24	100.36	91.29

of the melt. Its occurrence as inclusions in the majority of the other minerals supports this view (pl. XXIV, fig. B).

The optical properties are: $\omega = 1.636 \pm 0.003$; $\varepsilon = 1.633 \pm 0.003$.

Plate XIV. - Clusters of cubic pyrite crystals developed as penetration - twins on secondary calcite.

Ordinary light X 15.

In general <u>chondrodite</u> is observed as reddish-brown to greyish-green subhedral crystals more or less rounded and as irregular coarse to fine-grained aggregates scattered throughout the calcite.

In thin section it varies in colour from colourless to light yellow. Some crystals are pleochroic from neutral to pale yellow. On deeper coloured sections the pleochroism is intense. Polysynthetic twinning is common. Crystals of apatite occur as inclusions.

The chondrodite shows incipient alteration to serpentine with the dovelopment of secondary magnetite. Usually, however, it is remarkably fresh showing very little alteration. It occasionally shows mosiac re-crystallized rims round its own crystals, (pl. XXV, fig. A and B, pl. XXVI, fig. B).

The following optical properties have been determined:

Refractive indices, $\alpha = 1.611 \pm 0.003$, $\beta = 1.624 \pm 0.003$, $\gamma = 1.644 \pm 0.003$; orientation : $X \wedge \alpha = 27°$; axial angle: $2V\gamma = 78°$ measured, $2V\gamma = 73°$ calculated.

<u>Olivine</u> is far less abundant than chondrodite from which it is easily distinguished in hand-specimen by its cream-yellowish green colour. In thin section it is similar to chondrodite but the pleochroism, polysynthetic twinning and the lower refractive index of chondrodite provide a useful means of distinction.

It occurs predominantly as colourless fine-grained aggregates cemented by calcite. The individual crystals normally show polygonal outlines, (pl. XXVI, fig. A). In a similar manner to chondrodite, it shows alteration to serpentine with the development of secondary magnetite. The olivine is also remarkably fresh. It shows mosaic recrystallized rims in the same way as does chondrodite.

It has the following optical properties:
Refractive indices, $\alpha = 1.660 \pm 0.003$, $\beta = 1.677 \pm 0.003$, $\gamma = 1.694 \pm 0.003$; axial angle : $2V\alpha = 88°$ (measured), $2V\alpha = 90°$ (calculated). The optical properties indicate an average composition of Fo87 - Fa 13.

The mineralogical evidence suggests that olivine and chondrodite are early minerals formed after the apatite but before the bulk recrystallization of calcite.

There are two members of the mica family, namely <u>phlogopite</u> and <u>biotite</u>.

The phlogopite is predominant and in thin section is very pale yellow to colourless and forms irregular platy crystals. Hexagonal basal sections are seen occasionally. Thicker sections are pleochroic from neutral to pale yellow. It is easily distinguished from biotite by the general absence of pleochroism and by the interference figure obtained on basal sections. The figure is biaxial negative and as the axial angle is very small it approaches that of a uniaxial crystal.

Biotite occurs in the form of tabular plates which are reddish-brown in thin section and intensely pleochroic in shades of brown.

The mica plates are often strained and bent, and then show wavy extinction. The micas are replaced by copper sulphides and occur as inclusions in magnetite (pl. XXVIII, fig. A, pl. XXXVI, fig. B).

Hiemstra (1955) has identified the comparatively rare mineral <u>baddeleyite</u> (natural zirconia) in the carbonate member. It is entirely subordinate and in hand-specimen can occasionally be recognised as black flattened prismatic crystals of adamantine lustre.

In thin section it is easily recognised by its characteristic habit, high refractive index and brown colour. It is pleochroic in shades of brown. The high birefringence is masked by the body-colour. Crystals are generally between 0.05 mm and 1 mm in length. Polysynthetic twins showing vertical striae are common and interpenetrating twinned crystals occur (pl. XXVII, fig. B).

It is not always crystalline but is developed interstitially in chondrodite and calcite, which minerals it replaces. It is in turn replaced by magnetite and occurs as inclusions therein.

Hiemstra determined the following optical properties: Refractive indices: $\alpha = 2.136 \pm 0.005$, $\beta = 2.236 \pm 0.008$, $\gamma = 2.242 \pm 0.008$; $2V\alpha = 30° \pm 0.5°$, $X \wedge c = 13°$.

Maurice (1949) has stated that, although, zirconium minerals are apparently not found in hydrothermal veins they are typical pegmatitic minerals. The presence of baddeleyite in the carbonate member is therefore a useful geological thermometer, suggesting formation at temperatures of about 600°C.

<u>Pleonaste spinel</u> occurs as a subordinate constituent. It is found as inclusions in magnetite. The inclusions show the typical rhombic-outlines of octahedral crystals and in some instances the spinel is seen moulded on calcite inclusions (pl. XXVIII, fig. B). Spinel also

occurs as inclusions in calcite. Where these abut against magnetite the crystal faces are preserved. The crystals are colourless to green and isotropic. The optical properties are as follows:

$$n = 1.73 \qquad a_o = 8.103 \pm 0.002A.$$

The magnetite-spinel relations suggest spinel to be the earlier formed mineral.

Fluorite is present in minor amounts as purple isotropic crystals replacing calcite.

There are two varieties of serpentine. One is fibrous, the other massive. The latter is slightly iron-rich as compared with the former. Macroscopically it varies from dark green to clouded pale green and white. It is sometimes veined and mottled. Occasionally reddish specks and veins, which can be attributed to excess iron, are noticed. In thin section it is pale green to colourless.

The fibrous variety (pl. XXVII, fig. A) occurs mainly as an alteration product of chondrodite and olivine and is present, in some instances, as the cementing material healing brecciated carbonate.

Serpentine after olivine and chondrodite is a common feature. Serpentine, however, also occurs frequently at depth, and it is doubtful if all the serpentine is formed as the result of alteration of olivine or chondrodite.

3. The Opaque Minerals

Magnetite is the most abundant ore-mineral forming about 25 per cent of the carbonate member. Its distribution is, however, very variable. It occurs mainly as large coarse-grained masses with rounded to irregular outlines, often showing a bronze tarnish. Specks and grains, some of which show cubic outlines, are common. The magnetite rich areas vary from less than 0.1 mm to large masses. On an average they are 2 centimetres across but occasionally as much as 30 centimetres. Perfectly formed octahedra are seen at surface where they have been freed by weathering (pl. XV). Small octahedra, developed in a joint plane, were observed underground.

Plate XV. - Cluster of magnetite octahedra freed by weathering.

The magnetite generally takes a bad polish, having a dull-grey appearance of low reflectivity by reflected light (pl. XXXI, fig. B). It is isotropic and negative to the standard etch reagents.

Polished sections show the magnetite to be traversed by numerous irregular fractures which carry calcite and copper sulphides. The calcite merely heals the fractures but the early stages of replacement by chalcopyrite and valleriite can be observed. Inclusions of apatite, calcite, spinel, chondrodite, olivine, phlogopite and baddeleyite are common.

Replacement by valleriite and chalcopyrite is pronounced at the edges of magnetite masses adjacent to chalcopyrite. This is seen as residuals of magnetite at the margins of magnetite masses (pl. XXIX, fig. A), in an aggregate of chalcopyrite and valleriite. Veinlets of chalcopyrite and valleriite spread into the main body of magnetite and replace the latter (pl. XXXIV, fig. A). This is primarily due to valleriite with which chalcopyrite is associated as tiny inclusions but, in a few instances chalcopyrite not associated with valleriite was seen to replace magnetite in this manner.

Chalcocite replaces magnetite by irregular veins often as much as 2 mm in width. Occasionally valleriite is developed between the chalcocite and magnetite boundaries (pl. XXXIX, fig. A).

Overlapping crystallization is seen when the textural relationships of magnetite to calcite are considered. Normally magnetite replaces all the transparent minerals which occur as remnants therein. Many of these remnants show crystal form. The magnetite shows an interstitial relationship to calcite, often cutting the grain-boundaries of the latter. Fractures in the magnetite are healed by later calcite.

Although valleriite generally replaces magnetite in one instance contemporaneous crystallization was observed (pl. XXIX, fig. B, pl. XXX, fig. A). Veinlets consisting in part of magnetite and in part of valleriite fill fractures in chondrodite without any replacement. The veinlets show matching walls and originate from adjacent feeder areas of magnetite.

It has been suggested (Schwartz and Ronbeck 1940) that once formed magnetite is stable and only moderate evidence of replacement is observed.

Exsolution intergrowths of magnetite and ilmenite were observed in specimens from surface (Russell 1954). In the case, however, of samples from depth the magnetite was found to be homogeneous with respect to ilmenite; no exsolution growths of ilmenite were seen in it.

The available chemical analyses of magnetite from the carbonate member are given in table II.

These analyses suggest that the magnetite is either non-titaniferous or is extremely low in this respect. Gevers (1948), however, reports that three analyses by the Newcastle Iron Works indicate a TiO_2 content varying from 3.8 to 4.3 per cent. Brandt (1948) has described the magnetite of Loole Kop as titaniferous with ultramicroscopic staffs of spinel and exsolution lamella of ilmenite. A recent analysis of a representative sample of magnetite taken from the Phoscor Development Corporation stockpile gave a TiO_2 content of 4.9 per cent (result of analysis supplied by Phoscor). The material comes from a quarry in phoscorite situated on the western-flanks of Loole Kop.

Neither Gevers nor Brandt separate the 'limestone' from the magnetite-apatite-serpentine zone. Therefore, this apparent paradox may be due to a difference of titanium content of the magnetite occurring in the carbonate member and in the phoscorite respectively.

In order to clarify this, 53 magnetite samples from the carbonate member were submitted for spectrographic analyses of the titanium content. These samples represent firstly, the horizontal distribution of titanium oxide by taking samples at 50 feet intervals in the adit, and secondly, the vertical distribution by taking samples of core from bore-hole 7. In addition, nine samples of magnetite associated with phoscorite were selected. Three from the Phoscor quarry, and three each from two prospecting trenches on the southern slopes of Loole Kop.

The samples were first crushed to minus 115 mesh and the magnetite extracted with a bar magnet. This magnetite fraction was then treated with dilute hydrochloric acid to remove the carbonate impurity. Samples were oven-dried at 80°C for 24 hours. The results obtained are given in table III.

The magnetite obtained from occurrences of phoscorite gave the following percentages of titanium oxide:- 4.25, 5.1, 5.65, 5.05, 3.70, 3.10, 4.35, 4.80 and 4.30. A mean value of 4.48 per cent titanium oxide was obtained.

The relatively high titanium content of magnetite from the phoscorite as compared to that from the carbonate member is indicated by the results. A few examples (pl. XVI) of spectrographs obtained on five standards with a progressively decreasing titanium content and two samples each of the two varieties of magnetite are included. The titanium lines are marked by a cross. The difference in titanium content can be seen at a glance.

There is general agreement that magnetite as an ore mineral, as opposed to a rock mineral, is characteristic of high temperature deposits. The presence of magnetite in abundance indicates that deposition began at a high temperature of the order of 600°C (Edwards 1947). Schwartz and Ronbeck (1940) have shown that magnetite is generally the first metallic mineral to form. Furthermore, in magnetite - sulphide suites it precedes the sulphides in the paragenetic order.

In the suite under consideration the evidence suggests that the primary magnetite crystallization took place after the gangue minerals and before uranothorianite and copper sulphides crystallized.

TABLE NO. II. - CHEMICAL ANALYSES OF MAGNETITE FROM THE CARBONATE MEMBER

	1.	2.
SiO_2	4.65	
Al_2O_3	3.20	
CaO, MgO	4.60	
MgO	-	2.53
P_2O_5	1.67	
O(diff)	23.78	
Fe	62.10	
FeO	-	23.49
Fe_2O_3	-	73.40
TiO_2	-	0.54
NiO	-	0.01
V_2O_5	-	0.55
Totals	100.0	100.52

1. Anal: Lab. Geol. Sur. Source: A.L. Hall (1912)
2. Anal: A. Kruger. Source: H.D. Russell (1954)

TABLE NO. III. - TITANIUM OXIDE CONTENT OF MAGNETITE FROM THE CARBONATE MEMBER

(1) Horizontal Distribution - South Adit, East Face

Sample	TiO_2	Sample	TiO_2	Sample	TiO_2
1	0.35	7	0.13	13	0.29
2	0.43	8	0.07	14	1.60
3	0.50	9	1.90	15	3.10
4	0.36	10	1.40	16	1.70
5	1.20	11	2.10		
6	0.12	12	0.58		

Mean value = 0.99 per cent TiO_2

(2) Vertical Distribution - Bore-hole No. 7

Sample	Depth in feet	TiO_2	Sample	Depth in feet	TiO_2
1	20	0.06	19	953	0.03
2	79	0.10	20	1028	0.07
3	109	0.12	21	1053	0.06
4	140	0.13	22	1113	0.06
5	190	0.51	23	1164	0.62
6	240	0.66	24	1218	0.60
7	302	0.60	25	1255	0.07
8	354	0.34	26	1299	0.52
9	396	0.18	27	1350	0.76
10	456	0.49	28	1394	0.90
11	497	0.28	29	1466	0.92
12	554	0.70	30	1507	0.15
13	609	0.05	31	1551	0.86
14	659	0.10	32	1605	0.11
15	722	0.29	33	1649	0.17
16	754	0.02	34	1700	0.18
17	807	0.10	35	1757	0.07
18	836	0.51	36	1905	0.20

Mean value = 0.32 per cent TiO_2

Analyst: H.D. Russell.

Plate XVI

Plate XVI. - Qualitative spectrographic analysis of magnetite associated with phoscorite and the carbonate member

A-E Spectrographs of chemically analysed standards decreasing in TiO_2 percentage.

A 8.23, B 4.16, C 1.49, D 0.6, and E 0.15.

F-G Spectrographs of magnetite associated with phoscorite and having the following percentage of TiO_2.

F 4.25, G 5.1.

H-I Spectrographs of magnetite associated with phoscorit and having the following persentage of TiO_2.

H 0.60, I 0.20.

Experimental Procedure

Sample mixed with base (19 CuO +40 graphite powder) in the proportion of I :59.

Spectrograph. Hilger Large (Littrow type).

Quartz Optics.

Anode Excitation.

Sample in purified graphite anode. Depth of cavity 4 mm.
Diameter = 3 mm. Walls 0.5 mm.

Cathode - pointed, 3/16 inch purified carbon.

Arc gap. - 9 mm.

Exposure time. ∓ 80 secs.

Plate Ilford Halftone No. 50.

Development ID 13 for 2½ minutes at 23°C.

Analyst: H.D. Russell.

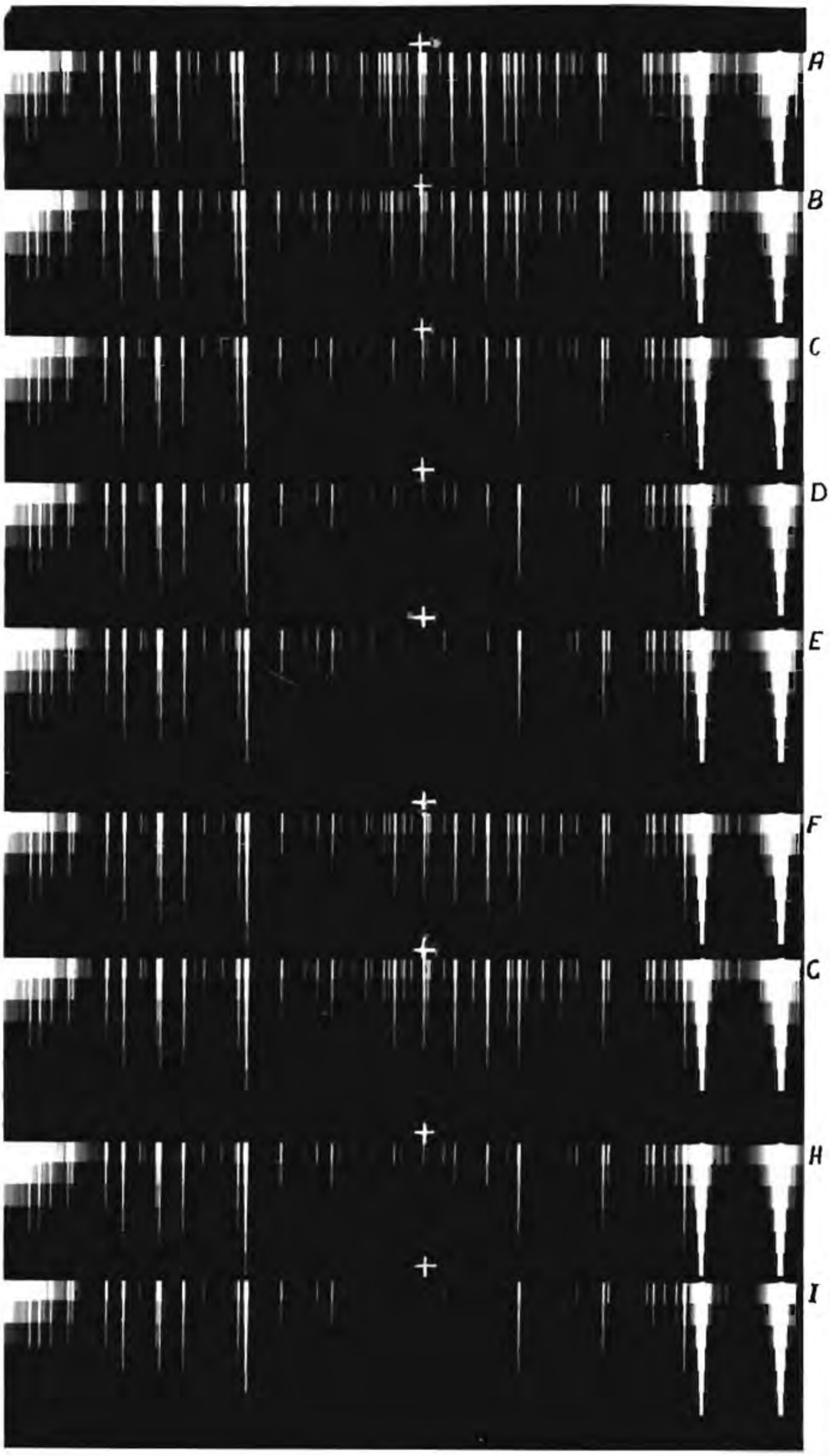


Plate XVI

Uranothorianite occurs mainly as well-formed euhedral crystals varying in size from less than 0.1 mm to as much as 2 mm across. On an average they are 0.3 mm across. In thin section they show cubic or triangular outlines (pl. XXX, fig. B). Interstitial fragments and veinlets are observed. Embayed outlines are frequent.

It resembles magnetite in physical and optical properties. It has approximately the same hardness and takes about the same polish. Grey by reflected light, the reflectivity is only slightly lower than that of magnetite. It is completely isotropic.

While magnetite does occasionally show cubic outlines the euhedral form of uranothorianite is, however, distinctive. The lower reflectivity is useful when uranothorianite is visible with magnetite in the microscope field but, otherwise is too slight to be of much help in identification.

Uranothorianite proved negative to the standard etch reagents.

Inclusions of calcite and apatite crystals are fairly common. The apatite inclusions occur as slender laths and basal sections with hexagonal outlines (pl. XXXII, fig. A).

Many of the uranothorianite crystals are surrounded by reaction-rims. These reaction-rims are not developed where the crystals flank apatite crystals. They are reddish in polarized light and while positive identification was not possible it is reasonable to assume that they are composed of a gummite-like material. Small irregular specks of a metallic substance of high reflectivity are associated with the reaction-rims and occasionally occur as inclusions and veins in the uranothorianite crystals. These specks are pale yellow in reflected light and appear isotropic. They could not be identified by x-rays as the specks are too minute to allow of clean material being obtained (pl. XXXI, fig. A).

The cubic outlines of uranothorianite crystals are preserved against magnetite (pl. XXX, fig. B). Occasionally euhedral crystals are seen developed in magnetite (pl. XXXI, fig. B). Many of the crystals show an interstitial relationship to magnetite.

The uranothorianite replaces calcite and other gangue minerals. Crystals cut across grain boundaries. Apparently corroded crystals are actually interstitial and are moulded on calcite and apatite (pl. XXXI, fig. A, pl. XXXII, fig. A).

Autoradiographs of selected high-grade radioactive specimens (pl. XVII - XXIII) show that whereas uranothorianite occurs predominantly in the calcite gangue, it can be expected to occur in association with the other gangue minerals and magnetite. In no instance, however, is it found associated with the sulphides. The best concentrations of uranothorianite are in breccia specimens.

The mineralogical evidence suggests that uranothorianite has a marked property of crystallinity and that the apatite, ferromagnesian silicates and the main calcite crystallization and magnetite preceded that of uranothorianite. The uranothorianite tends to be associated with the more easily replaced calcite (pl. XXX, fig. B).

The occurrence of pyrrhotite in the carbonate member, has not previously been reported. It is one of the less abundant sulphides and is present as irregular granular aggregates in a manner similar to that of the other sulphides.

Inclusions of gangue minerals together with numerous fractures cause it to take a bad polish. It is pleochroic from cream-yellow to pinkish-brown and strongly anisotropic from blueish-grey to brown. The following etch reactions were obtained:

HNO_3. Fumes tarnish otherwise negative.

HCl. Periphery of drop turns brown, otherwise negative.

KOH. Periphery of drop slowly stains brown. Permanent stain.

KCN, $FeCl_3$. Negative.

$HgCl_2$ Stains brown. Rubs off. Doubtful.

The etch reactions agree with those given by Short (1940).

Inclusions of apatite and calcite are the most common. It replaces the gangue minerals and is in turn replaced by valleriite (pl. XXXII, fig. B). Replacement by valleriite develops from fractures into the pyrrhotite.

Lamellar twinning was observed in one polished section of pyrrhotite (pl. XXXIII, fig. A). These twins are best observed in polarized light as they do not show simultaneous extinction with the main pyrrhotite mass. Etching these twin-lamella gave the same reactions as for pyrrhotite.

On some portions of pyrrhotite parallel orientated wavy lenses were observed. Occasionally they were arranged to form a herringbone structure. These lenses suggest exsolution intergrowths of gamma and beta pyrrhotite (Scholtz 1936; Ramdohr 1950).

Subordinate pentlandite is seen as irregular granular residuals in pyrrhotite. The relations observed do not represent typical exsolution textures nor could any evidence suggesting replacement be obtained.

Originally Schneiderhöhn (1922) and van der Veen (1925) were of the opinion that pentlandite formed in pyrrhotite entirely by the unmixing of a solid solution. Newhouse (1927) and Scholtz (1936), independently, reached the conclusion that the association can be either due to exsolution or the segregation of the minerals in the liquid phase.

Schwartz (1937) has stated that while pyrrhotite is common without visible pentlandite, the latter is not found without pyrrhotite or chalcopyrite. Since the two minerals are so closely related they must have formed contemporaneously or very nearly so, and the normal relationship is as grains of pentlandite equigranular with pyrrhotite and as smaller grains and stringers along the border of pyrrhotite grains.

Hewitt (1938) has shown, experimentally, that while large masses of pentlandite in pyrrhotite are the products of crystallization of immiscible liquid, lenses or residuals within pyrrhotite grains are the result of unmixing.

The pentlandite-pyrrhotite relations in the carbonate member, therefore, suggest unmixing of a solid solution. That solid solution occurs at temperatures from 425 to 450°C has been shown by Newhouse (1927) and Hewitt (1938).

Chalcopyrite is associated as laths in the pyrrhotite and as granular intergrowths at the margins of pyrrhotite aggregates. Some isolated grains of pyrrhotite are enclosed by a rim of chalcopyrite.

The paragenesis of pyrrhotite and chalcopyrite is an established one. Various investigators have stated that the relationship is close and while to a certain extent crystallization is partly contemporaneous, the bulk of the chalcopyrite is somewhat later than the pyrrhotite (Schwartz 1937).

Hewitt (1938) has shown experimentally that chalcopyrite and pyrrhotite are capable of forming two types of solid solutions depending on the temperature of formation:

(a) Pyrrhotite dissolves in chalcopyrite at temperatures of about 300°C, when the two minerals react to form chalcopyrrhotite which forms a very fine intergrowth with chalcopyrite in an aureole about pyrrhotite. (Uytenboogaardt, 1951, has suggested that chalcopyrrhotite is a superfluous name and that the mineral is an isotropic form of cubanite, Ramdohr's cubanite II).

(b) Above 600°C, chalcopyrite dissolves in pyrrhotite and upon unmixing forms orientated laths in pyrrhotite.

The chalcopyrite-pyrrhotite relations observed in the carbonate member suggest, therefore, that solid solution was formed at temperatures of about 600°C. Slow cooling probably allowed segregation of chalcopyrite to the margins of pyrrhotite aggregates, where unmixing gave rise to laths and granular intergrowths.

It is known that the only common minor elements that substitute for iron in the pyrrhotite structure are cobalt and nickel. Verne and others (1955) have suggested that if either the cobalt or nickel content of pyrrhotite is greater than 1 per cent, an included mineral of cobalt or nickel might be present. Semi-quantitative spectrographic analysis of pyrrhotite showed the relative proportions of nickel to cobalt to be 4:3. Mineralogical examination failed to disclose the presence of a cobalt or nickel mineral.

The literature suggests that high temperature and pressure are necessary in the formation of pyrrhotite, restricting its occurrence to magmatic, pyrometasomatic and hydrothermal deposits. It is regarded as definite evidence of high temperature of formation and as such is a useful geological thermometer indicating a temperature of formation above 600°C.

Pyrrhotite is seen to replace the gangue minerals, but its relation to the ore minerals, except chalcopyrite, could not be established due to lack of suitable material. The general sequence of paragenesis, observed normally in high temperature magnetite-sulphide suites, suggests pyrrhotite to be early in the sulphide suite. (Schwartz and Ronbeck 1940).

Pentlandite is entirely subordinate, but its distribution is fairly wide. It only occurs in association with chalcopyrite and pyrrhotite as granular residuals.

It is isometric and can be distinguished from chalcopyrite by its lighter yellow colour and slightly higher reflectivity. It is somewhat harder than chalcopyrite (pl. XXXIII, fig. B). When included in pyrrhotite it appears white in contrast. On etching with nitric acid, it tarnishes and slowly stains brown. A doubtful reaction was observed with hydrochloric acid. All other reagents gave negative results. The identification was confirmed by x-rays.

The relation of pentlandite to pyrrhotite has previously been discussed. The chalcopyrite-pentlandite relations will be discussed under the section dealing with chalcopyrite.

<u>Chalcopyrite</u> is the most abundant copper sulphide and as such is easily recognised in hand-specimen. It shows no crystal form and occurs as irregular massive patches and 'schlieren'. Under the microscope tiny specks and streaks are observed, the latter often showing a vein-like form.

It is easily recognised by its brass-yellow colour, high reflectivity and ease with which it can be scratched by a needle. It is slightly anisotropic from greyish-blue to yellow. It tarnishes when etched with nitric acid, but is otherwise negative to the standard reagents.

Chalcopyrite is associated with the other copper sulphides and contains residuals of cubanite and pentlandite. It occurs in association with bornite. The textural relationship varies from mutual relations, where the two minerals show mutual boundaries (pl. XXXIV, fig. B), with gashes of bornite occurring in chalcopyrite and vice versa, to the development of exsolution lamella in the crystallographic planes of bornite (pl. XXXVII, fig. B). Grating textures of bornite in chalcopyrite, as the possible result of unmixing, are common (pl. XXXVIII, fig. A). It is found associated with chalcocite to a lesser degree. The chalcocite may possibly have formed at the expense of bornite disintegration. It occurs as tiny specks in valleriite (pl. XXIX, fig. A).

It replaces all the gangue minerals generally along planes of weakness, such as fracture and cleavage, from which planes it spreads into the body of the replaced mineral (pl. XXXVI, fig. B, pl. XXXVII, fig. A). The carbonate member is frequently brecciated and chalcopyrite then heals the brecciated fragments without evident signs of replacement (pl. XXXV, fig. B, pl. XXXVI, fig. A). Bornite, chalcocite, pentlandite and magnetite are associated with this chalcopyrite. It replaces magnetite along grain boundaries and to a lesser extent by a series of ramifying veinlets following fractures. Residuals of magnetite grains in chalcopyrite are observed. The smaller grains of magnetite are often enclosed by a rim of chalcopyrite.

The pentlandite-chalcopyrite relations are similar to those observed in the association pyrrhotite-pentlandite. In some instances, however, cracks in the pentlandite, are filled with chalcopyrite.

While some of the pentlandite is contemporaneous with chalcopyrite a continuation of deposition of chalcopyrite beyond that of pentlandite is suggested.

<u>Cubanite</u> occurs associated with chalcopyrite as

irregular granular inclusions, varying in size from tiny specks to areas as much as 2 mm across, in a similar manner to pentlandite. It was not observed associated with pyrrhotite or other sulphides. In one instance a cubanite residual was seen in chalcopyrite associated with bornite (pl. XXXIV, fig. B, pl. XXXV, fig. A).

The cubanite is strongly pleochroic from cream-yellow to brownish-yellow; anisotropic from pinkish-brown to brownish-yellow. Its higher reflectivity and marked anisotropism distinguish it from chalcopyrite. It is easily distinguished from pentlandite, occurring in chalcopyrite, by its anisotropism, inferior hardness and the good relief shown by pentlandite in polished sections.

The following etch reactions were obtained:

HNO_3	Negative on the major portion of the mineral, in places stains light brown.
HCl, KCN, $FeCl_3$, KOH.	Negative.
$HgCl_2$.	Mineral stains yellowish-brown. Rubs off. Doubtful.

The etch reactions together with the optical properties confirm the identification of cubanite.

It is known that a chalcopyrite-cubanite solid solution forms above 450°C, and on unmixing gives rise to the development of parallel laths of cubanite in the crystallographic planes of chalcopyrite.

The observed relations in the carbonate member are not typical of exsolution, but in the absence of replacement textures, contemporaneous crystallization of cubanite and chalcopyrite is suggested.

Although bornite is subordinate to chalcopyrite, it is frequently seen. It is similar to chalcopyrite in its mode of occurrence. It is easily distinguished by its characteristic colour, pinkish-brown when fresh, and purple on tarnished surfaces. It is isotropic.

The etch reactions obtained are not in exact agreement with those given by Short (1940). The reactions compare as follows:

Reagent	Etch obtained	Etch reactions according to Short.
HNO_3	Effervesces; mineral stains brown.	Effervesces; mineral stains yellowish-brown; sometimes develops etch-cleavage which tends to form a brick-like pattern.
HCl	Negative	Negative
KCN	Negative	Negative
$FeCl_3$	Brings out brick-like cleavage	Stains orange
KOH	Negative	Negative
$HgCl_2$	Negative	Negative.

Bornite is usually associated with chalcopyrite as granular intergrowths showing mutual relations (pl. XXXIV, fig. B). It occurs as the host to chalcopyrite laths developed in its crystallographic planes (pl. XXXVII, fig. B) and as laths and grating textures in the crystallographic planes of chalcopyrite (pl. XXXVIII, fig. A). Chalcocite is sometimes associated with these intergrowths. It occurs as graphic intergrowths with chalcocite (figured by Russell 1954, pl. XXXIII, fig. 1). It occasionally fills cracks in cubanite.

It replaces the gangue minerals and magnetite in the same way as chalcopyrite. It replaces chalcopyrite (pl. XXXVIII, fig. B), and is in turn replaced by chalcocite.

Bornite and chalcopyrite are known to form solid solutions at temperatures above 475°C in which solid solution either may act as the host. It has also been shown experimentally that more or less granular mixtures of the two may represent a breakdown of a solid solution that existed at higher temperatures. (Schwartz 1931).

The textures observed range from crystallographic intergrowths, granular intergrowths, mutual boundaries, mutual relations to replacement. These relations suggest that bornite, a characteristic intermediate temperature mineral deposited below 500°C in deposits of magmatic or hydrothermal origin (Edwards 1947), is in part contemporaneous with, and in part later than chalcopyrite.

Gilbert (1925) has suggested that bornite occurs in high-temperature deposits only where iron is not abundant. Schwartz (1937) finds that while magnetite and bornite are intimately and abundantly associated in some copper ores, he is of the opinion that Gilbert's generalization is a good one since the association is very rare. The copper mineralization at Phalaborwa, therefore, represents another instance of this unusual association.

<u>Chalcocite</u> is far less abundant than chalcopyrite and bornite. Its mode of occurrence is similar to that of chalcopyrite, but the tendency to occur as irregular veins is far more pronounced.

Under the microscope it is characterised by its greyish-white to bluish-grey colour, high reflectivity and softness. Generally isotropic, some specimens show weak anomalous anisotropism probably due to excess pressure exerted during polishing.

The chalcocite occurs as coarse to extremely fine-grained aggregates. The latter usually occur as veins (pl. XXXIX, fig. A). On etching with nitric acid, both the fine and coarse-grained varieties show the characteristic parallel etch-cleavage of hexagonal hypogene chalcocite (pl. XXXIX, fig. B) formed above 105°C (Buerger 1941). It occurs as residuals in intergrowths of chalcopyrite and bornite, possibly as the result of disintegration of bornite. Chalcopyrite and bornite are associated with it as granular aggregates showing mutual boundary relations.

Chalcocite is seen to replace bornite along fractures. Rim replacement is also common. Narrow zones of chalcocite around bornite areas separate them from the gangue minerals. (The vein chalcocite is normally not associated with bornite). It replaces all the gangue minerals and magnetite.

Much of the chalcocite associated with bornite appears distinctly blue. This may be due to a small percentage of dissolved bornite, or alternatively a surface film as the result of oxidation, or, as has been suggested by Wandke (1953), due to dragging and smearing during polishing.

Bornite-chalcocite solid solutions are known to form at temperatures from 175 - 225°C (Schwartz 1928) and that either can figure as the host. Various investigators have stated that graphic intergrowths and mutual relations are not definite criteria of either exsolution or replacement. The textural relationships observed, however, suggest that while some of the chalcocite is contemporaneous with bornite, the bulk is later than bornite.

Valleriite is of widespread distribution mainly as fine laminated aggregates in veinlike form. These veins vary from less than 0.1 mm to 2 mm in width and occasionally swell out into rounded to irregular areas often 2 centimetres across. The latter are mainly in calcite. The valleriite is responsible for the bronze tarnish seen on some of the magnetite.

It is massive and in polished section is seen to have a fibrous habit. Its physical properties are similar to those of graphite and in hand-specimen it is brownish-bronze in colour similar to that of pyrrhotite, but darker. It polishes with difficulty on account of its softness.

In polished sections it is cream to brownish-yellow and is pleochroic in these colours. It is strongly anisotropic from yellowish-grey to reddish-brown.

The mineral is not listed by Short and the etch reactions given by Uytenboogaardt (1951) are not in accord with those obtained on material from Phalaborwa.

The reactions compare as follows:

Reagents	Reaction obtained	Uytenbogaardt.
HNO_3	Immediate effervescence and mineral stains black. Permanent.	Slowly stains slightly; washes clean.
HCl	Negative	Negative
KCN	Negative	Negative
$FeCl_3$	Negative	Darkens slightly brings out grain boundaries.
KOH	Negative	Negative
$HgCl_2$	Negative	Stains brownish-black; rubs clean.

The identification was confirmed by x-rays. Spectrographic analysis (Russell 1954) shows Cu, and Fe to be the main constituents with subordinate Mg and Al. A chemical analysis for these elements is given in Table No. IV.

Table No. IV. - CHEMICAL ANALYSIS OF VALLERIITE

	Per cent
Cu	18.91
S	21.65
Mg	10.80
Ni	0.25
FeO_3	28.10
Al_2O_3	8.00

Analyst: Abraham Kruger, Division of Chemical Services.

The valleriite contains tiny specks of chalcopyrite. Inclusions of gangue minerals are common. It replaces all the gangue minerals, magnetite and the sulphides, particularly chalcopyrite and bornite. Replacement is generally by a system of ramifying veinlets (pl. XXXIV, fig. A) which cut the mutual boundaries of adjacent minerals. It is usually developed at the common boundary of chalcopyrite and magnetite. There are residuals of chalcopyrite and magnetite in the valleriite which shows a preference to replace magnetite (pl. XXIX, fig. A). Contemporaneous crystallization of magnetite and valleriite is observed healing fractures in chondrodite with only minor signs of replacement (pl. XXIX, fig. B, pl. XXX, fig. A).

Valleriite has been reported from a number of high-temperature copper deposits. Edwards has stated that the mineral is stable at temperatures of 410°C, but valleriite included in chalcopyrite is converted to pyrrhotite and chalcopyrite if heated above 225°C.

The relations observed indicate that the mineral was the last sulphide to crystallize and the association of it with chalcopyrite suggests that it formed at temperatures below 225°C.

Four sulphide samples were examined spectrographically for the presence of silver, nickel and cobalt. The semi-quantitative results gave the following relative proportions:

	Ag.	Ni.	Co.
Chalcopyrite	-	+++	+
Bornite	++	-	-
Chalcocite	+++	-	-
Valleriite	-	+++	+

Analyst: H.D. Russell.

Bornite and chalcocite were examined microscopically for the presence of a silver mineral with negative results.

C. Paragenesis

The mineralogical information shows clearly that we are concerned with mineralization at high temperatures. The mineral association and the observed textural relations are, however, not conclusive enough to establish if the mineralization is magmatic, pyrometasomatic or hydrothermal in origin. That the earlier formed gangue minerals were followed by the metallic oxides which were in turn followed by the sulphides is clear. This paragenetic order does not represent any notable departure from the paragenesis common to deposits with these affinities.

The time relationships between the various minerals which could be established, have already been discussed.

The following paragenetic stages are indicated:

1. Apatite, dolomitic-calcite (continuing) olivine and chondrodite, phlogopite and biotite.

2. Spinel, baddeleyite, magnetite, uranothorianite, fluorite.

3. Pyrrhotite, pentlandite, cubanite, chalcopyrite, bornite, chalcocite, valleriite, serpentine.

4. Serpentine, pyrite, secondary calcite and copper oxides.

With the exception of the minerals listed under group four, no interruption of deposition is indicated solely on the basis of the mineralogical evidence.

V. - THE DISTRIBUTION OF THE ECONOMIC CONSTITUENTS

A. General

The mineral rights of the ground occupied by the carbonate member are held by the Crown, Transvaal Ore Company and the Phoscor Development Corporation. The various holdings are shown in figure 6.

The carbonate was prospected by drilling vertical bore-holes to prove depth and inclined bore-holes to fix the outer limits of the zones of high radioactivity in the solid rock. Since the information from bore-holes could not give a sufficiently clear picture of conditions at depth an adit was driven from the phoscorite into the carbonate member.

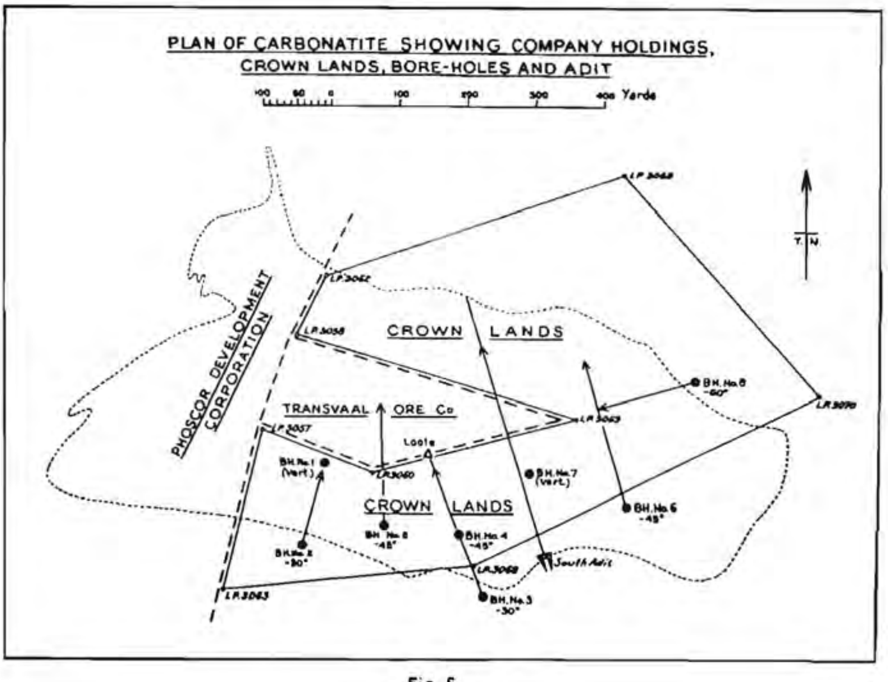


Fig. 6

A diagrammatic representation of the relationship between the prospecting as at February, 1956 and the isorad plan is shown in figure 7.

Wet assays for copper and phosphate were done by the Government Metallurgical laboratory and physical assays for uranothorianite by the Geological Unit, Atomic Energy Board. The results of these latter assays are expressed as lbs per ton equivalent uranium oxide[1].

Although the magnetite of Loole Kop had been regarded as titaniferous and therefore refractory, microscopic studies of polished sections and spectrographic analyses indicate, as has already been pointed out, that the titanium content is low. For this reason magnetite was estimated by visual assay. Control was obtained by means of a measuring tape.

The detailed assay results are not included. They are, however, available on the files of the Geological Unit, Atomic Energy Board. For purposes of comparison the assay results are presented graphically in the form of distribution diagrams, figs. 8 to 16 and 18.

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1. It is customary to express the results of physical radiometric analyses done against uranium standards in terms of the equivalent uranium oxide as lbs per ton. That is, although the activity of a sample may be due to both uranium and thorium, the analysis is given in lbs per ton uranium oxide which is equivalent to the total radioactivity of the particular sample.

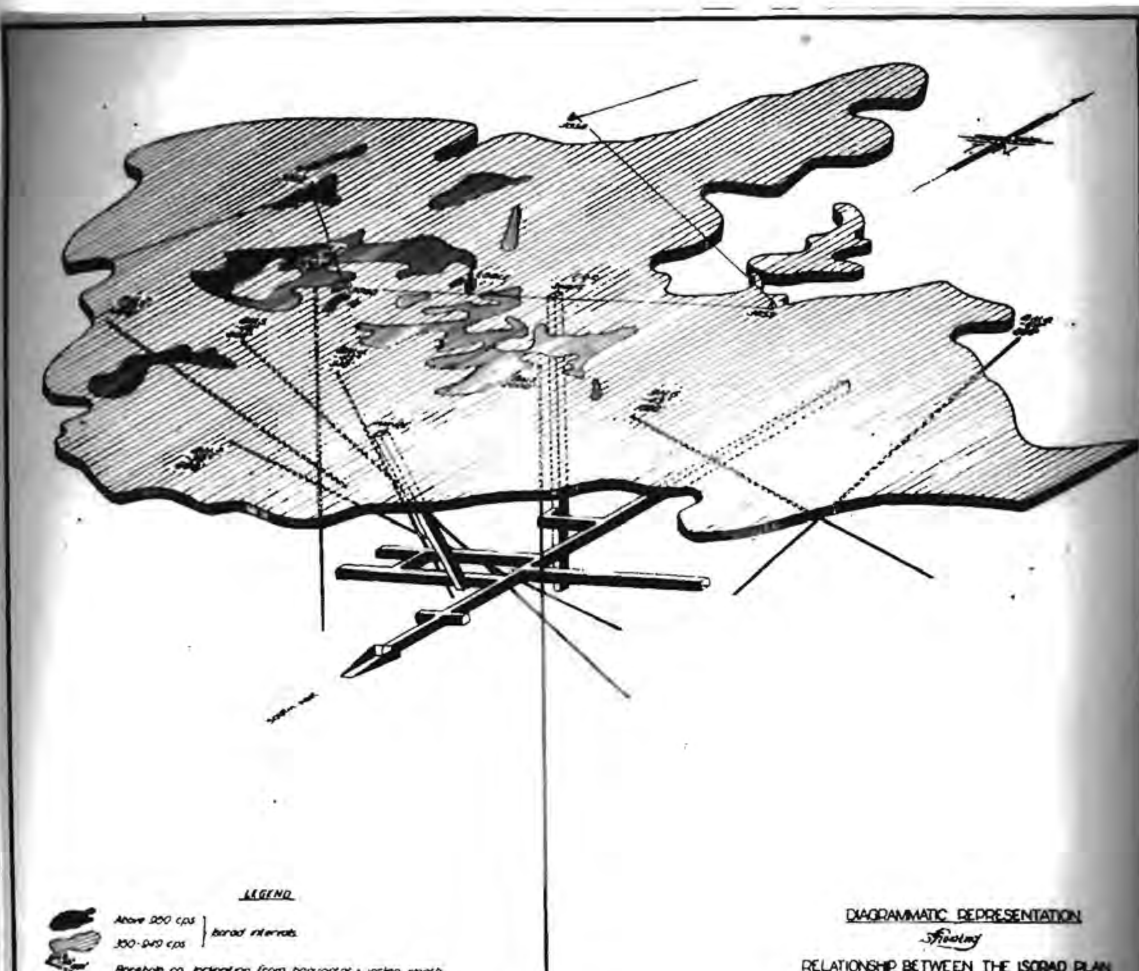
LEGEND
Above 950 cps
350-949 cps
Borehole no, inclination from horizontal & incline depth
DIAGRAMMATIC REPRESENTATION
Showing
RELATIONSHIP BETWEEN THE ISORAD PLAN
AND THE PROSPECTING

Fig. 7.

B. Prospecting Results

1. Vertical Bore-holes

Two vertical bore-holes, 1 and 7, were drilled to prove the continuity at depth of carbonate. The bore-holes were selected at points where high surface activity was found. They are spaced 870 feet apart. The positions are shown in fig. 6.

Radioactivity logs were made so that the distribution of uranothorianite as indicated by logging and physical assay could be compared. The results are given in figures 8 and 9 in which copper and phosphate values are also shown.

Bore-hole No. 1 was stopped at 743 feet in dolerite after having intersected 717 feet of mineralized carbonate. The radioactivity log (fig. 8) shows a change in level at approximately 310 feet below which depth the mean activity drops. No importance attaches to this change in radioactivity level as the bore-hole does not give a representative picture of the whole body because of the vertical alignment of the mineralization. The log cannot, therefore, be taken as indicating a decrease of activity with depth.

Several corresponding points and zones of peak radioactivity marked A, B, C and D are shown by both the log and the plot of uranothorianite assay values, but no systematic variation is apparent. The plot of copper values shows a tendency for the best copper mineralization to occur over the section, down to 310 feet, where the maximum radioactivity was obtained. Lower phosphate values were obtained over this section.

Bore-hole No. 7 intersected 1893 feet of mineralized carbonate, at which depth drilling was stopped. The core was mineralized throughout the length of the bore-hole. There were no indications that the mineralization does not continue beyond 1893 feet.

The radioactivity log (fig. 9) shows the presence of several high activity anomalies. The agreement between the log and equivalent uranium values by assay is only fair. Since radioactivity logging is of quantitative significance only if the active material is evenly distributed through the host rock it follows, from the poor agreement, that uranothorianite will prove to be sporadically distributed in the carbonate member.

The vertical distribution of copper, phosphate and magnetite bear no apparent relation to the zones, marked A, B, C, D and E where the main concentrations of uranothorianite were found.

2. Inclined Bore-holes

All the evidence points to mineralization following a near-vertical trend. The cross-section intersected in a vertical bore-hole under these conditions is small giving little or no idea of the structure and the general distribution of value. A series of inclined bore-holes were, therefore, drilled inwards towards the centre of the carbonate member.

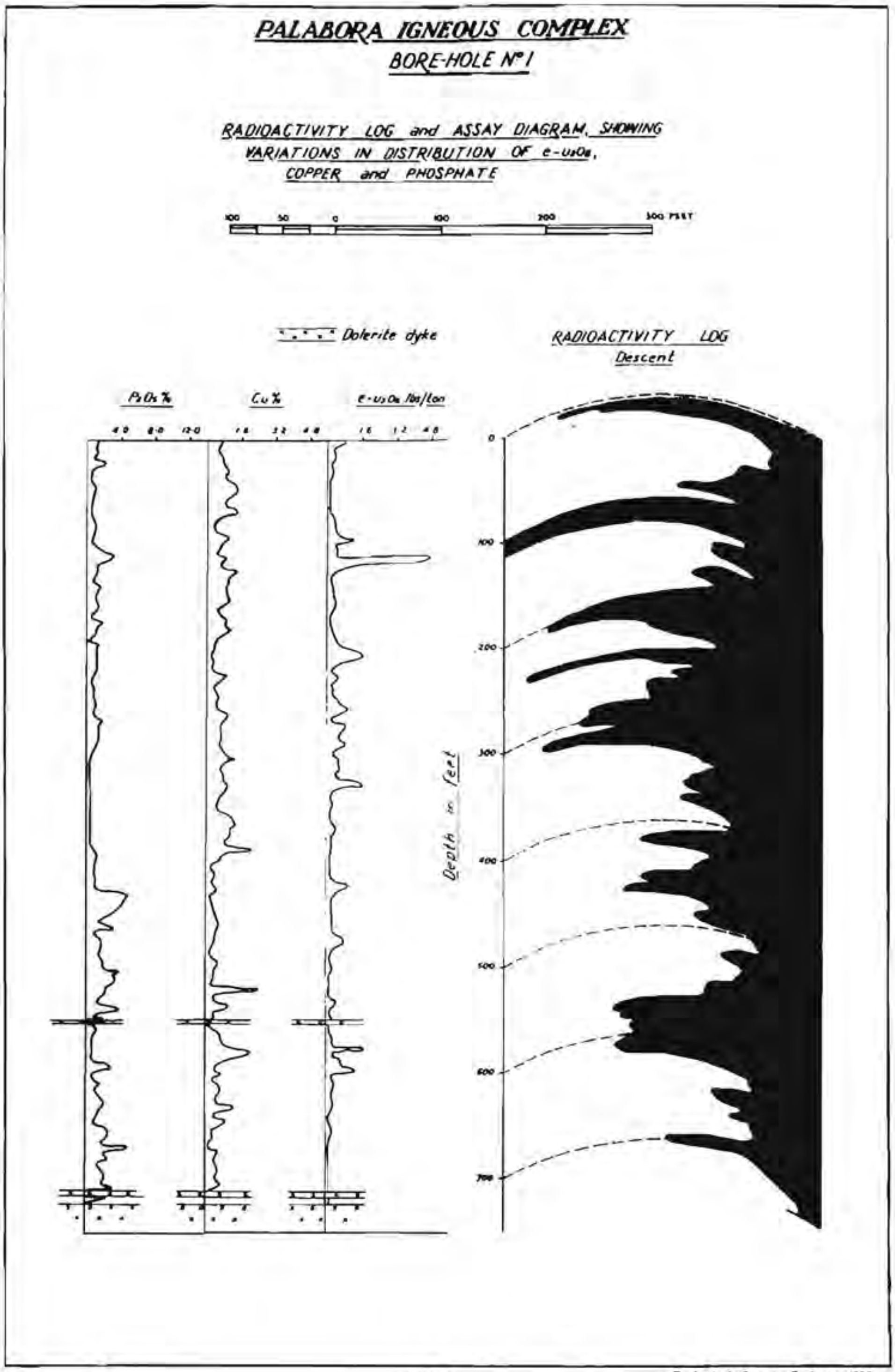

FIG. 8.

Geological Survey, Pretoria, 1954

PALABORA IGNEOUS COMPLEX

BORE-HOLE No 7

RADIOACTIVITY LOG AND ASSAY DIAGRAM SHOWING VARIATIONS IN DISTRIBUTION OF e-U_3O_8, COPPER, PHOSPHATE AND MAGNETITE

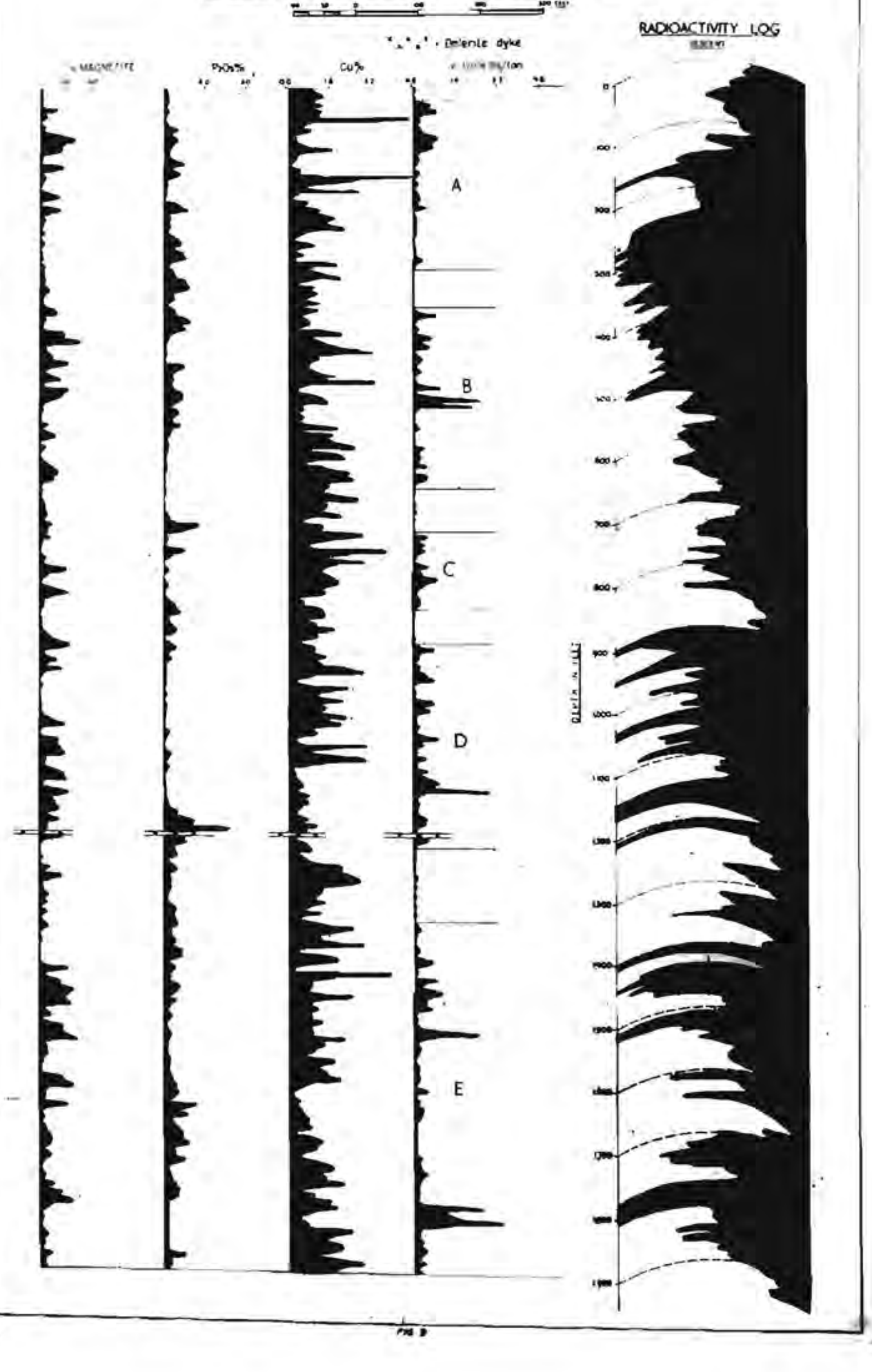

FIG 9

The positions, inclination and direction of these bore-holes in relation to the carbonate-phoscorite contact are shown in figure 6. The sites were selected to intersect as much as possible of the ground over which high radioactivity anomalies were found (fig. 5).

For purposes of comparison sample lengths have been corrected to the horizontal and the assay results presented diagrammatically on a horizontal plane. Mean assay values calculated over various lengths are plotted in a circle on the respective distribution diagrams. The scale of value is plotted on the vertical axis and corrected horizontal distance on the horizontal axis (figs. 10 - 15).

The value distribution diagram for <u>Bore-hole No. 2</u> (fig. 10) shows that there are no significant uranothorianite or copper values at the phoscorite - carbonate contact. The contact was sharp and near vertical.

VALUE DISTRIBUTION DIAGRAM
BOREHOLE Nº 2 - 30°

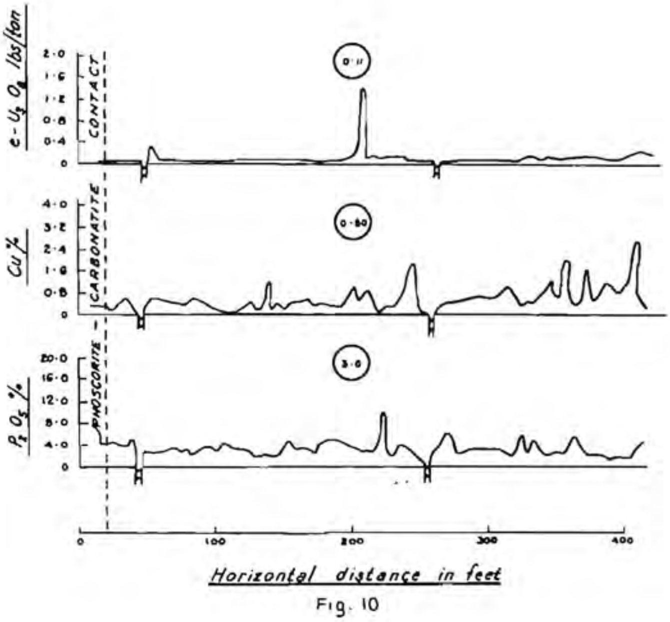

Fig. 10

The graph of equivalent uranium assays shows low values throughout the ground intersected. Exceptions are sporadic highs at 55 and 230 feet. A slight tendency for values to increase towards the centre of the carbonate member can be discerned.

Copper values vary within wide limits. A definite tendency for copper content to increase with increasing distance from the phoscorite - carbonate contact can be seen.

The graph of phosphate values shows a distinct drop on passing into carbonate. A fairly constant concentration of apatite occurs over the length of the borehole.

The value distribution diagram for Bore-hole No. 3 (fig. 11) allows two subdivisions to be made. For convenience these divisions are referred to as the 'inner' and 'outer' zone. In this and subsequent distribution diagrams the zones are separated by a vertical broken line.

Apatite is concentrated over the first 370 feet of carbonate. At 370 feet from the dyke - carbonate contact, the abrupt decrease in apatite content is striking.

Uranothorianite shows minimum concentration over the first 275 feet of carbonate, from which point onwards there is a higher concentration. From 355 to 570 feet a zone carrying higher uranothorianite values, coincides closely with the low phosphate zone.

Copper mineralization is distributed throughout the carbonate intersected. Values show a fairly wide scatter from the overall mean value, but a general increase is observed with increasing distance from the dolerite - carbonate contact. The best copper mineralization, 1.45 per cent, coincides approximately with the low apatite section from 355 to 570 feet.

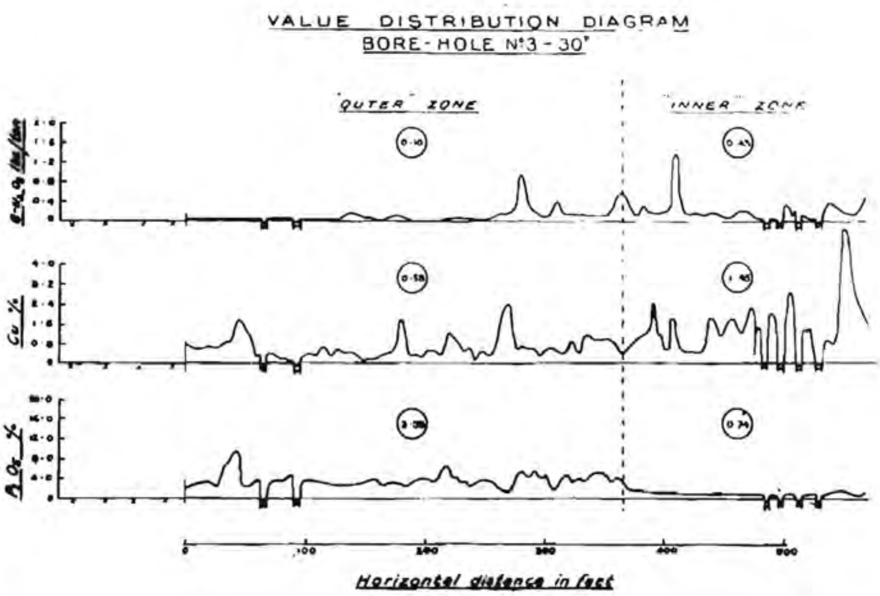

Fig. 11.

Figure 12 shows Bore-hole No. 4 to have passed through a zone of maximum apatite concentration and entered a zone of lower values at a horizontal distance of 160 feet. Individual values from 160 feet onwards show little variation from the mean value.

Although copper mineralization is again distributed throughout, the main concentration coincides almost exactly with the low apatite zone. Uranothorianite values are concentrated over the section where major copper and minor apatite mineralization occurs.

VALUE DISTRIBUTION DIAGRAM
BOREHOLE N°4-45°

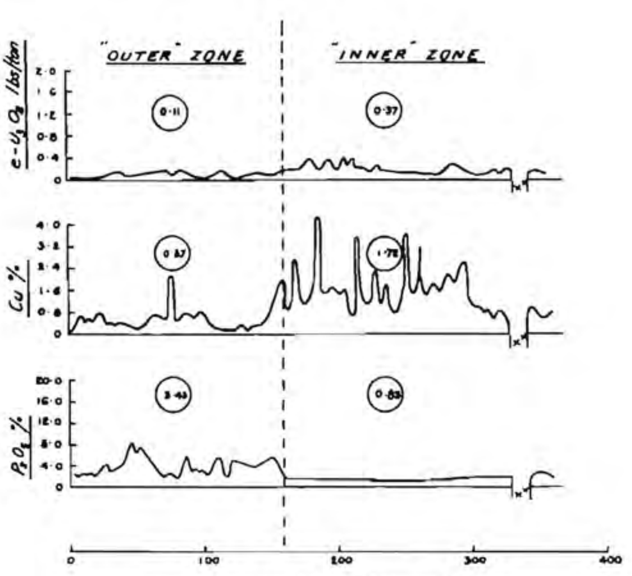

Fig 12

The phosphate distribution graph of Bore-hole No. 5 (fig. 13) shows an abrupt drop in values at 80 feet. The zone of low values beyond this point does, however, show values somewhat higher than the average. The presence of these can perhaps be attributed to localised phosphate enrichment in ground where, in general, low values are normal.

There is a tendency for lower uranothorianite and copper values to occur in the zone where apatite is best concentrated.

This was the first instance where visual assay of magnetite content was made. Results are available over the last 360 feet. Magnetite is seen distributed throughout. The values show wide variations from the mean of 19 per cent.

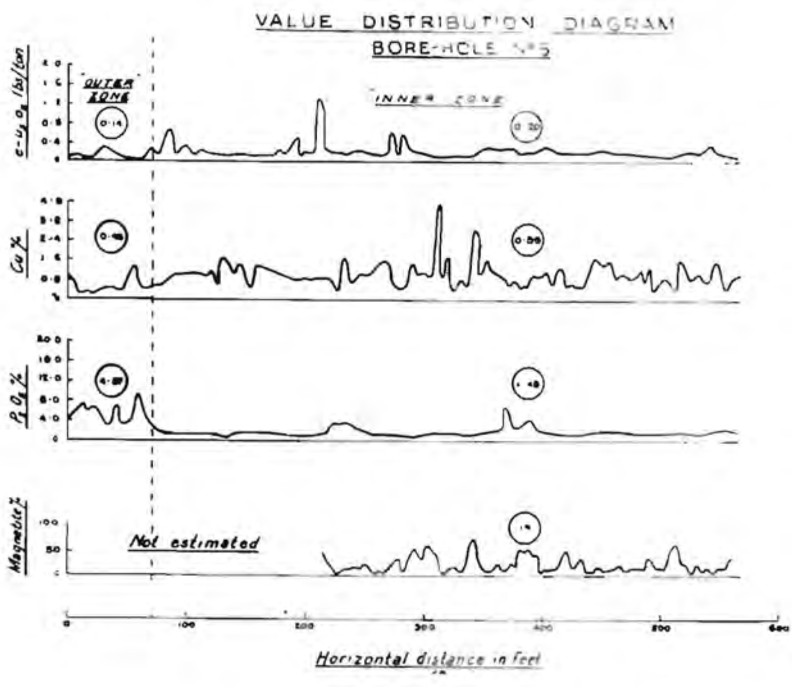

Fig. 13

In the case of Bore-hole No. 6, the value distribution diagram (fig. 14) does not give as clear a picture as in previous instances. The zone of low phosphate values is obscured, but the distribution of uranothorianite shows that the bore-hole passed through a zone of low values and into a zone of higher radioactivity at a horizontal distance of 406 feet. This zone persisted for 147 feet, beyond which the bore-hole disclosed 156 feet of carbonate carrying little uranothorianite. The zones of low radioactivity show sporadic enrichment by uranothorianite.

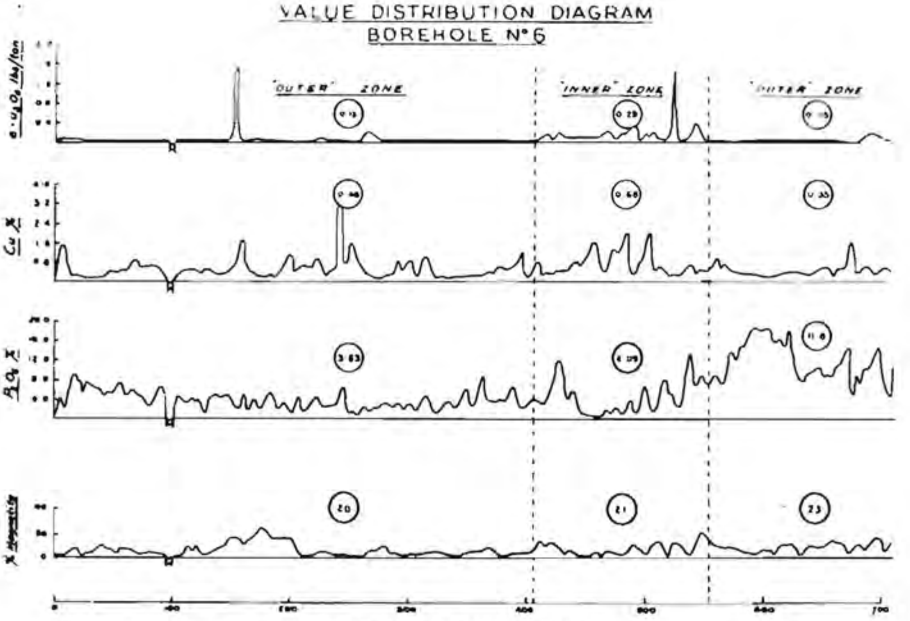

Fig. 14

Phosphate values do not show an abrupt drop over the zone indicated by concentration of uranothorianite. The values do, however, show a general lower level. Beyond 555 feet high phosphate values coincide with low uranothorianite concentration.

Copper mineralization is fairly evenly distributed throughout the bore-hole. It is best concentrated throughout the zone where the maximum concentration of uranothorianite was found.

The magnetite content varies within wide limits and its distribution shows no relationship to that of phosphate or copper and uranothorianite.

<u>Bore-hole No. 8</u> commenced in phoscorite and passed into carbonate at an incline depth of 73 feet. The contact was again sharp and near vertical.

Negligible concentrations of uranothorianite and copper were found in the phoscorite intersected. Phosphate values were, however, high.

Relatively high phosphate values (fig. 15) were found throughout the carbonate intersected. Contrary to expectations uranothorianite and copper values were not low. A general tendency for the higher copper values to coincide with low phosphate values is, however, evident from the distribution diagram. The distribution of magnetite is similar to that found in other inclined bore-holes.

VALUE DISTRIBUTION DIAGRAM
BORE-HOLE Nº 8

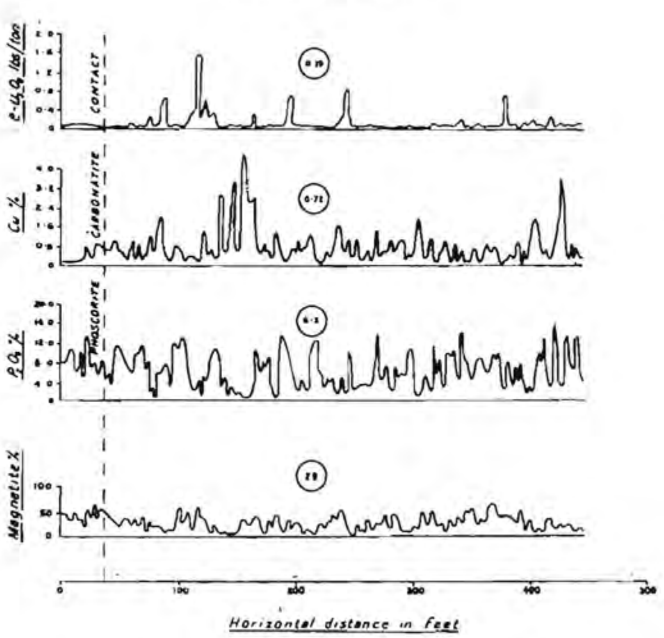

Fig. 15

The portion of ground over which Transvaal Ore Company hold the mineral rights (fig. 6) was prospected by the company. A series of inclined bore-holes were drilled from their northern boundary, south towards the common boundary with Crown lands (fig. 22).

Assay results are available for uranothorianite and copper from their bore-holes T.O.C. 1, 2, 3 and 5. The results are presented in figure 16, where copper and equivalent uranium oxide values are plotted for each bore-hole. Where no assay values were returned the graphs are not completed.

Figure 16 shows that on the basis of the distribution of uranothorianite two zones can be established in the case of all four bore-holes. The northern part of the carbonate member is characterised by a poor concentration of radioactive material. The usual sympathetic relation between copper and uranothorianite is apparent. This does not always apply in the case of individual samples, but exists in the broader sense.

3. South Adit

The information obtained from the south adit was supplemented for economic reasons, while the adit was being advanced, by probing the carbonate member with a series of cross drives set-off at right angles to the adit. The position of the adit and ground opened-up by February, 1956 are shown in figure 17.

As the cross drives are developed along the strike of east-west trending mineralization a study of the values disclosed is unlikely to provide any evidence relating to the general distribution. The information obtained from them has accordingly been excluded and only the adit values are considered.

The assay results conform to those obtained by drilling in so far as the copper-uranothorianite-phosphate distribution is concerned (fig. 18). The following points are worthy of mention:-

1. Phosphate is predominantly concentrated over the first 307 and the last 410 feet sampled. In other words in the periphery of the carbonate member.

2. Copper is distributed throughout the carbonate member. The best values were found from 307 to 566 feet over which section phosphate values were low.

3. The higher uranothorianite values were obtained over that section showing the best copper and the poorer phosphate values. This section is characterised by prominent jointing and brecciation.

4. Magnetite is distributed throughout and shows a wide variation in values. Its distribution shows no relation to that of the other possible economic constituents.

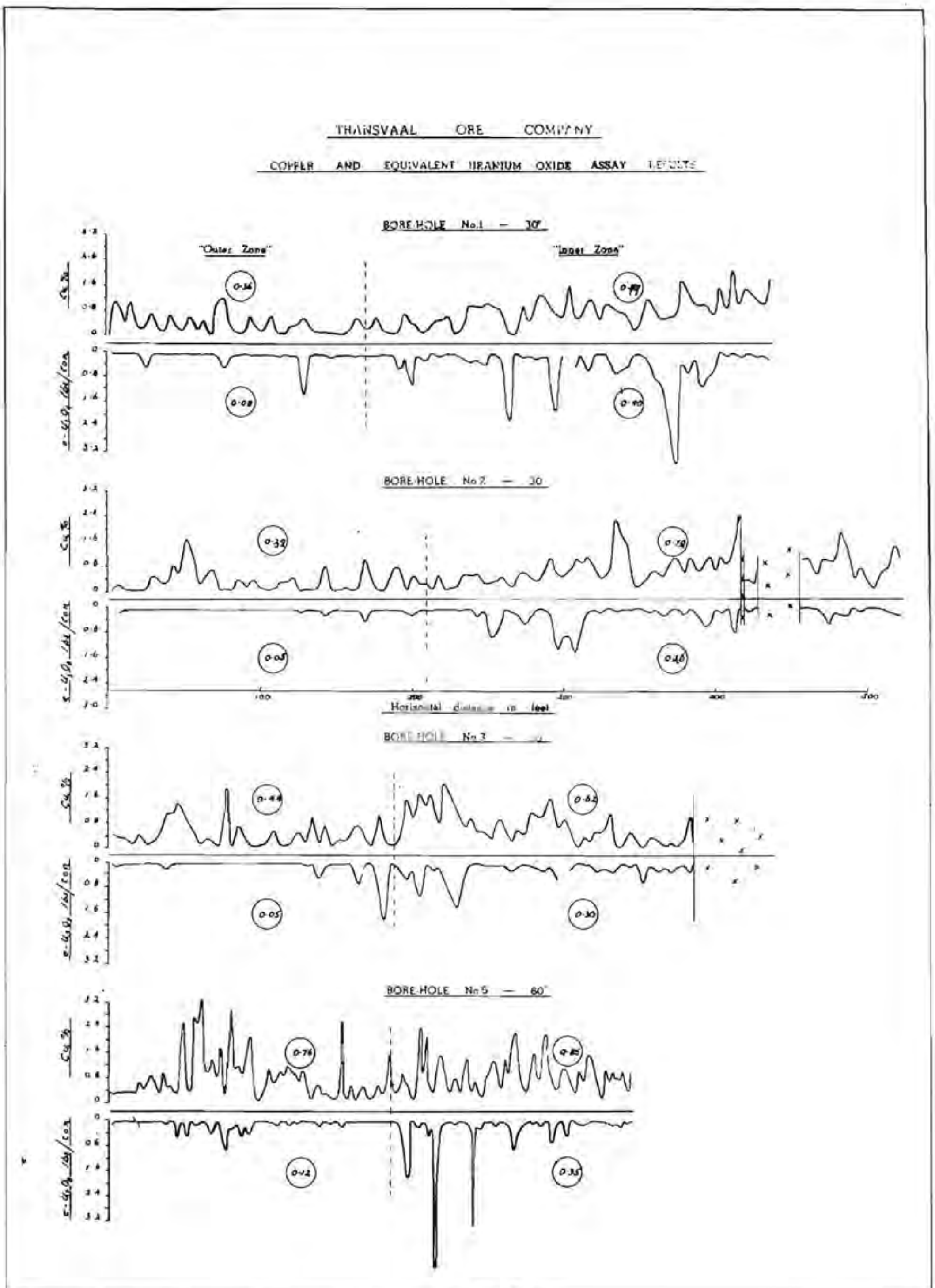

Fig. [redacted] 16

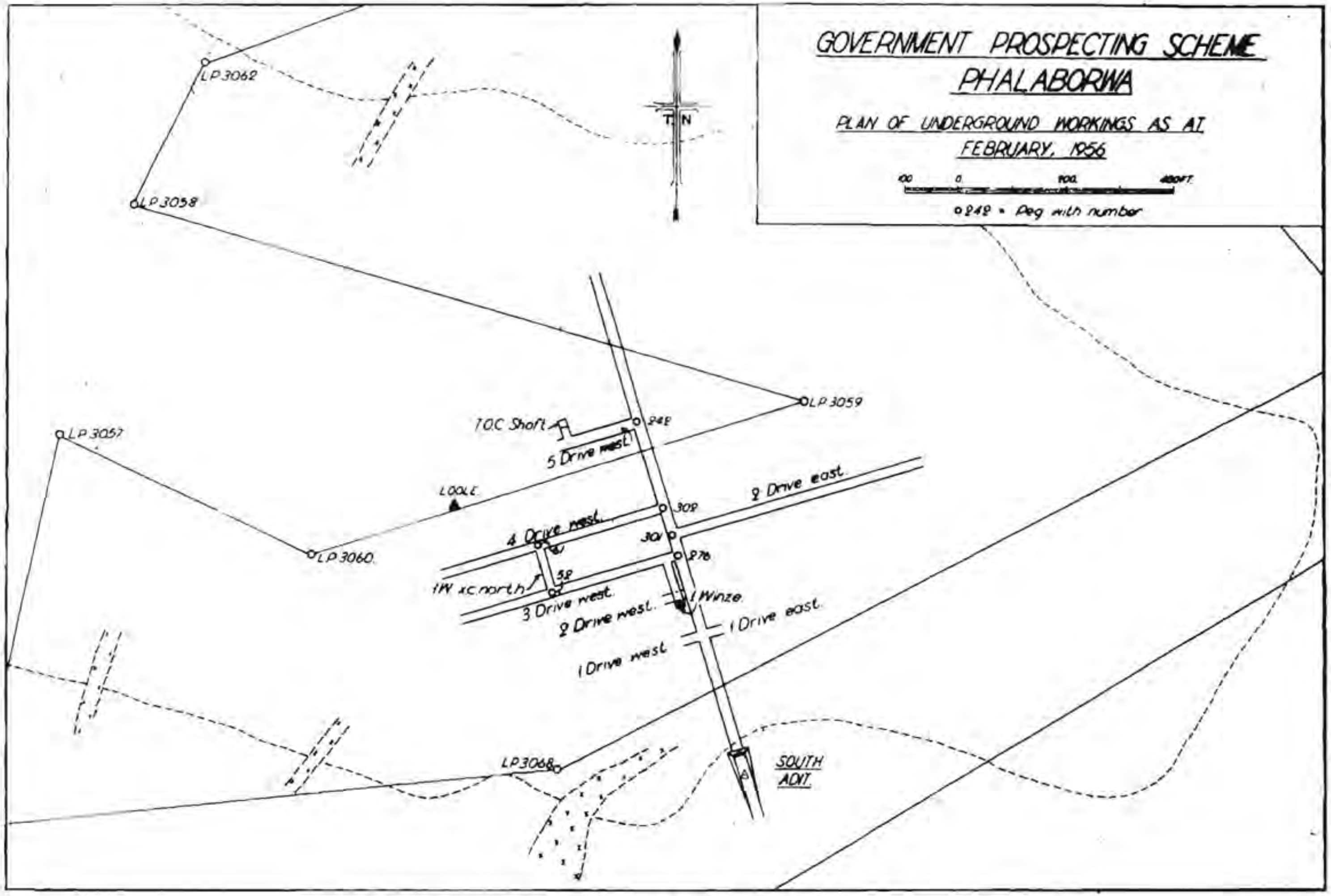
GOVERNMENT PROSPECTING SCHEME
PHALABORWA
PLAN OF UNDERGROUND WORKINGS AS AT
FEBRUARY, 1956
100 0 100 400FT.
o 248 = Peg with number
T N
LP 3062
LP 3058
LP 3059
LP 3057
LP 3060
LP 3068
T.O.C. Shaft
5 Drive west
248
309
301
276
58
2 Drive east
4 Drive west
1W xc.north
3 Drive west
2 Drive west
1 Winze
1 Drive east
1 Drive west
SOUTH
ADIT

Fig. ■ 17

VALUE DISTRIBUTION DIAGRAM

SOUTH ADIT, EAST FACE

AS AT 1ST FEBRUARY 1956

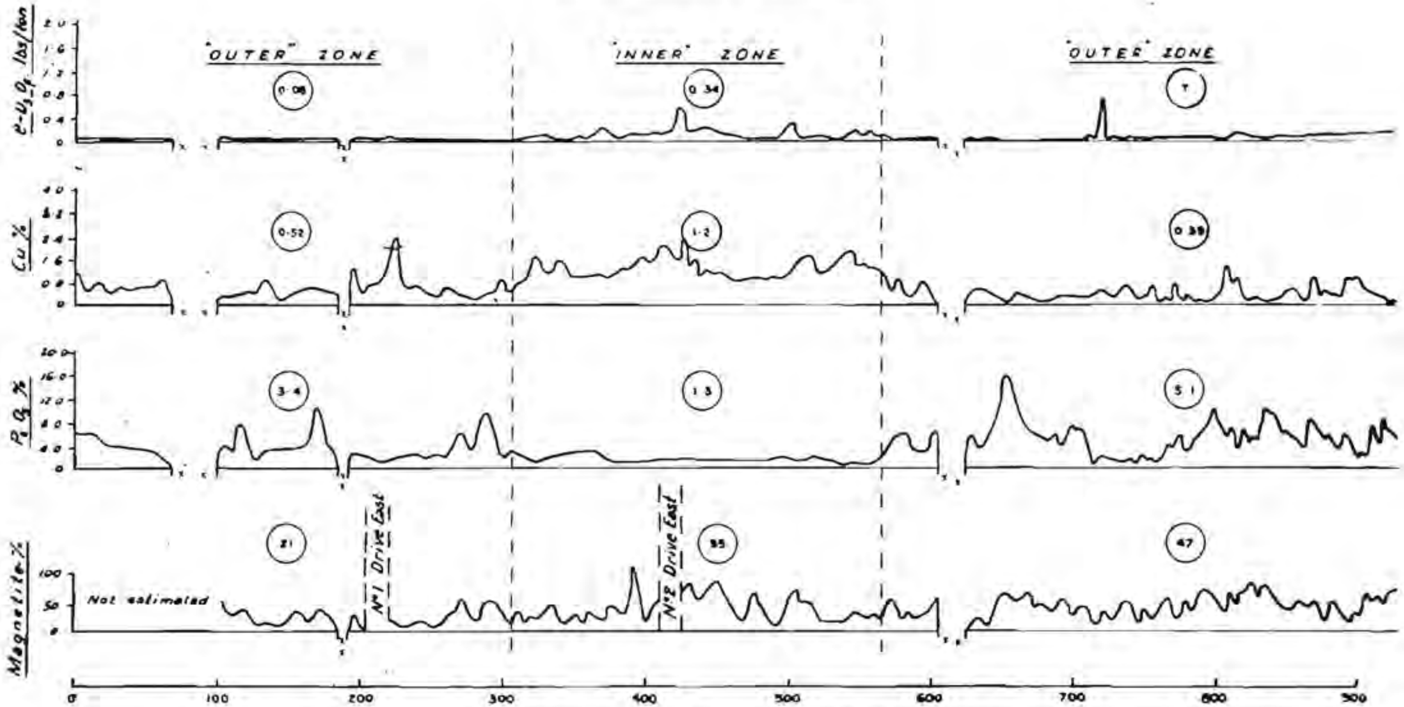

Fig. 18

C. The Continuity of Mineralization

Vertical drilling has shown that the carbonate core extends in depth to at least 1893 feet and that no change in mineral content occurs down to this depth. Some idea of the attitude of mineralization can be gained by comparing the value distribution diagrams plotted for bore-holes 3 and 4.

The assay results are compared in figures 19, 20 and 21, which show the distribution of phosphate, copper and uranothorianite in the two bore-holes, respectively. The bore-holes are shown in their correct relationship to the topography. The graphs are plotted corrected to the horizontal and the 'outer' and 'inner' zone, as indicated by the phosphate values, projected on to the line of the bore-holes.

The bore-holes were drilled in the same vertical plane; bore-hole 3 passed 229 feet vertically below the collar of bore-hole 4. The bottoms of the bore-holes are separated by a vertical distance of 78 feet.

The diagrams are very similar, particularly in the case of the phosphate distribution (fig. 19), where the abrupt drop in values clearly marks the change from the 'outer' to 'inner' zone. The 'inner' zone here coincides closely with ground over which high radioactivity anomalies were found by radioactivity surface mapping (fig. 5).

The distribution of copper values (fig. 20) does not follow exactly the cut-off between the 'outer' and 'inner' zone shown by the comparison of phosphate values. Nevertheless it is very close. In both bore-holes copper is distributed throughout, but the main concentrations coincide well with low phosphate values. The remarks made in the case of copper distribution can be equally applied for uranothorianite.

These comparisons suggest that mineralization can be expected to show similar trends with depth and to be vertically disposed. A worth-while comparison of the assay values returned from both inclined drilling and aditing should thus be obtained if phosphate, copper and uranothorianite values are projected to a horizontal plane at the same level as the adit. The results of such projections are presented diagrammatically on composite assay plans, figures 22, 23 and 24. The information depicted on these assay plans represents only the main features replotted from the distribution diagrams.

The diagrams support the contention that the carbonate member can be subdivided into two zones. An 'outer' zone characterised by the best concentration of apatite with low concentrations of copper and uranothorianite, and an 'inner' zone where the latter constituents are mainly concentrated with low or negligible apatite values.

The outline of the 'inner' zone is drawn to fit the distribution of uranothorianite, copper and phosphate and is repeated on all three diagrams.

No information, except the surface distribution of uranothorianite as indicated by the isorad map (fig. 5) is available for the ground west of line pegs 3057 and 3058 (fig. 6). The boundary is shown dotted over this section in conformity with anomalies indicated by the isorad map.

The outline has been drawn through ground north of line pegs 3057, 3060 and 3059 (fig. 6) on the basis of information obtained from bore-holes drilled by the Transvaal Ore Company (T.O.C. 1, 2, 3 and 5). No phosphate values are available and in figure 24 the line has been drawn through this section on the indications obtained from uranothorianite and copper distribution.

It must be emphasised that the outline shown, does not define the 'inner' zone at any particular level. It merely represents a composite picture inferred from the available information obtained at various depths and projected to the same level as the adit. The 'inner' zone represents that part of the carbonate member characterised by the best concentration of uranothorianite and copper sulphides. The carbonate was most likely readily replaced by late mineralizing solutions, so that the shape of the 'inner' zone will probably be found to change at different levels. The general shape, however, should conform to the outline shown. It forms, broadly speaking, a kidney-shaped area following a east-west trend within the carbonate member.

PHOSPHATE VALUES
DIAGRAM SHOWING CONTINUITY IN DEPTH
BORE-HOLES Nº 3 AND 4

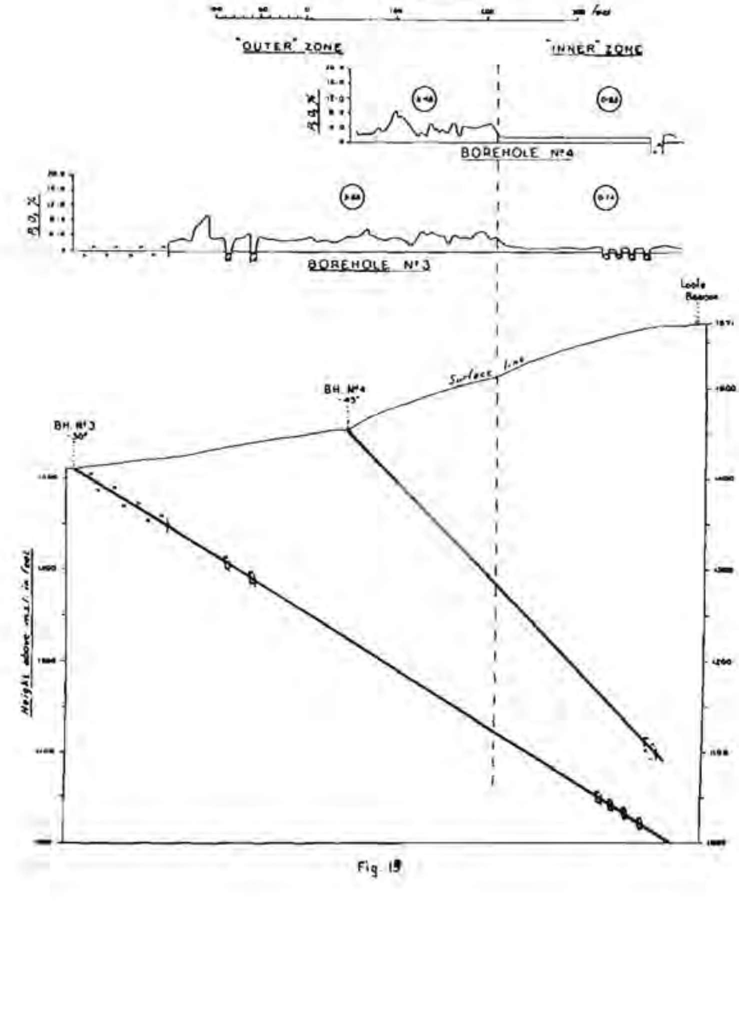

Fig. 19

COPPER VALUES
DIAGRAM SHOWING CONTINUITY IN DEPTH
BORE-HOLES Nº 3 AND 4

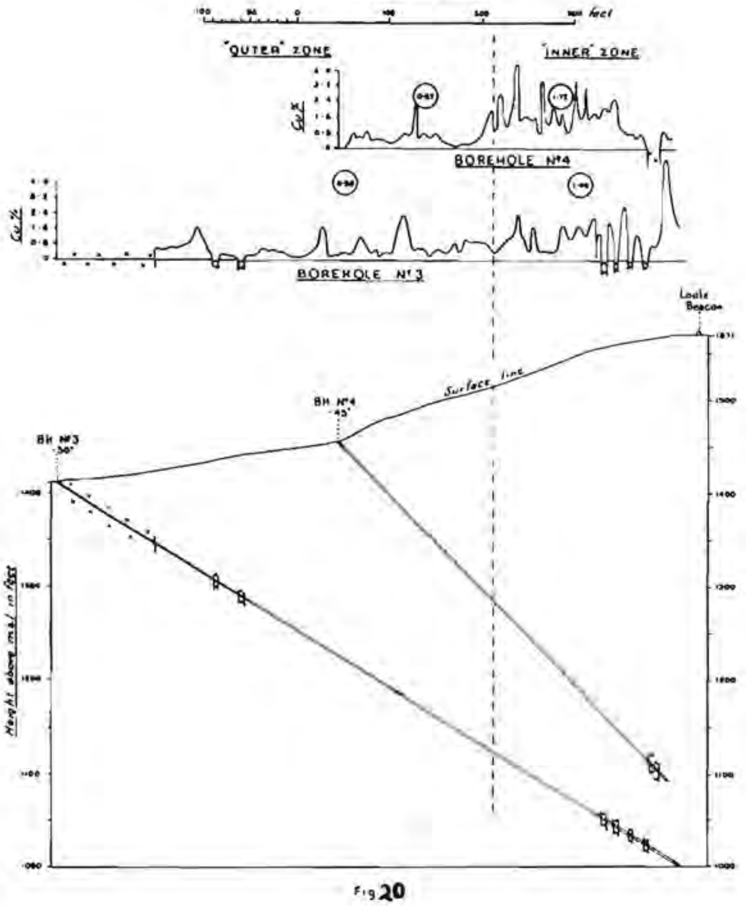

Fig 20

EQUIVALENT URANIUM OXIDE VALUES
DIAGRAM SHOWING CONTINUITY IN DEPTH
BORE-HOLES Nº 3 AND 4

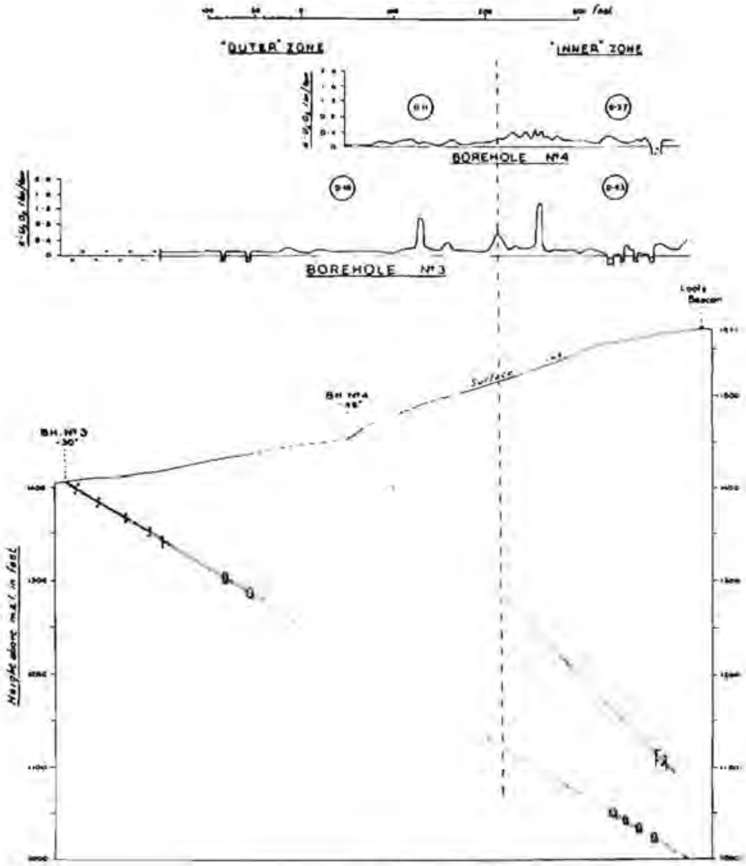

Fig 21

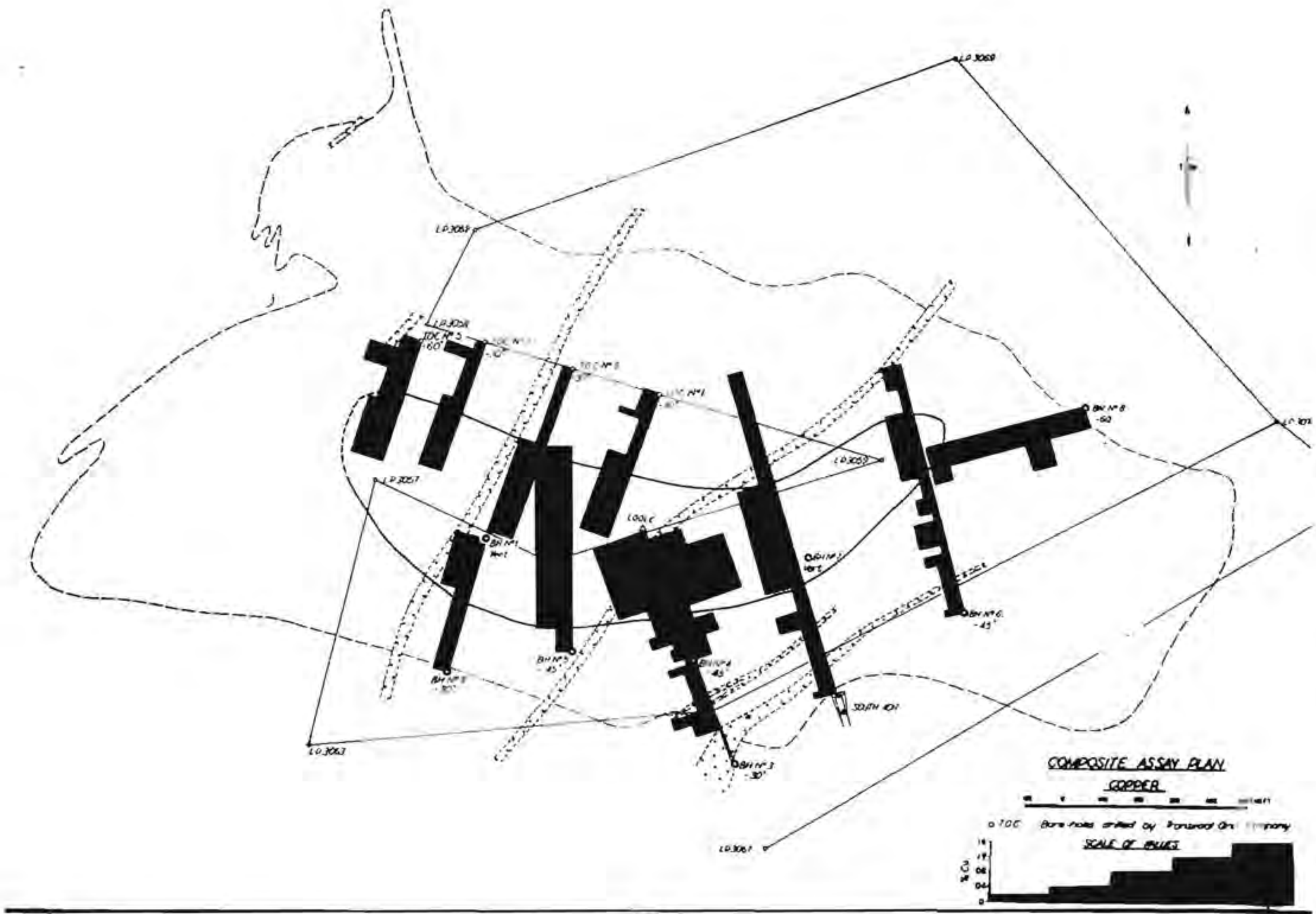
COMPOSITE ASSAY PLAN
COPPER
o T.D.C. Bore-holes drilled by
SCALE OF VALUES
% Cu
SOUTH ADIT

Fig 22.

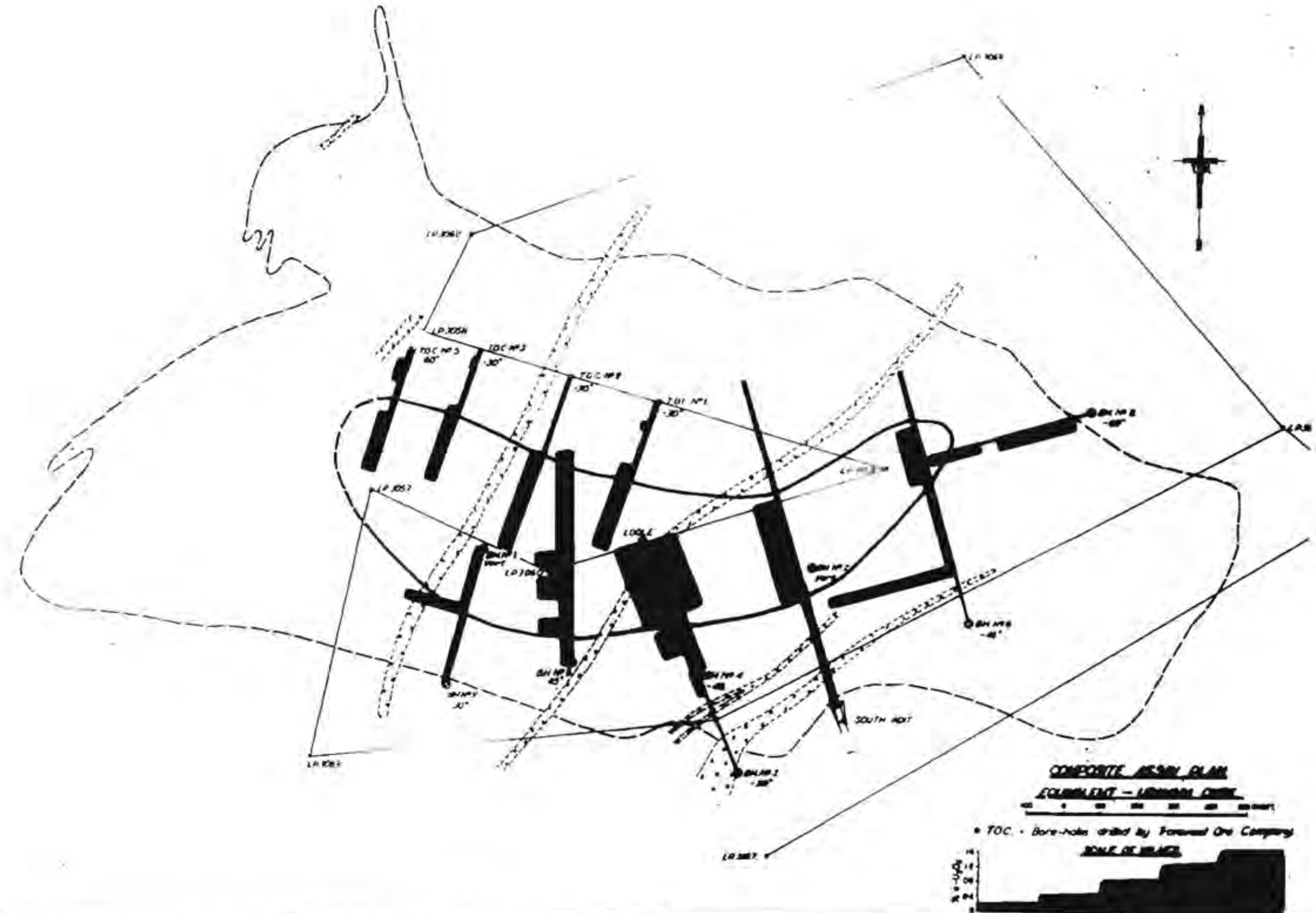
LODE
SOUTH ADIT
• TOC. - Bore-holes drilled by Transvaal Ore Company

Fig 23

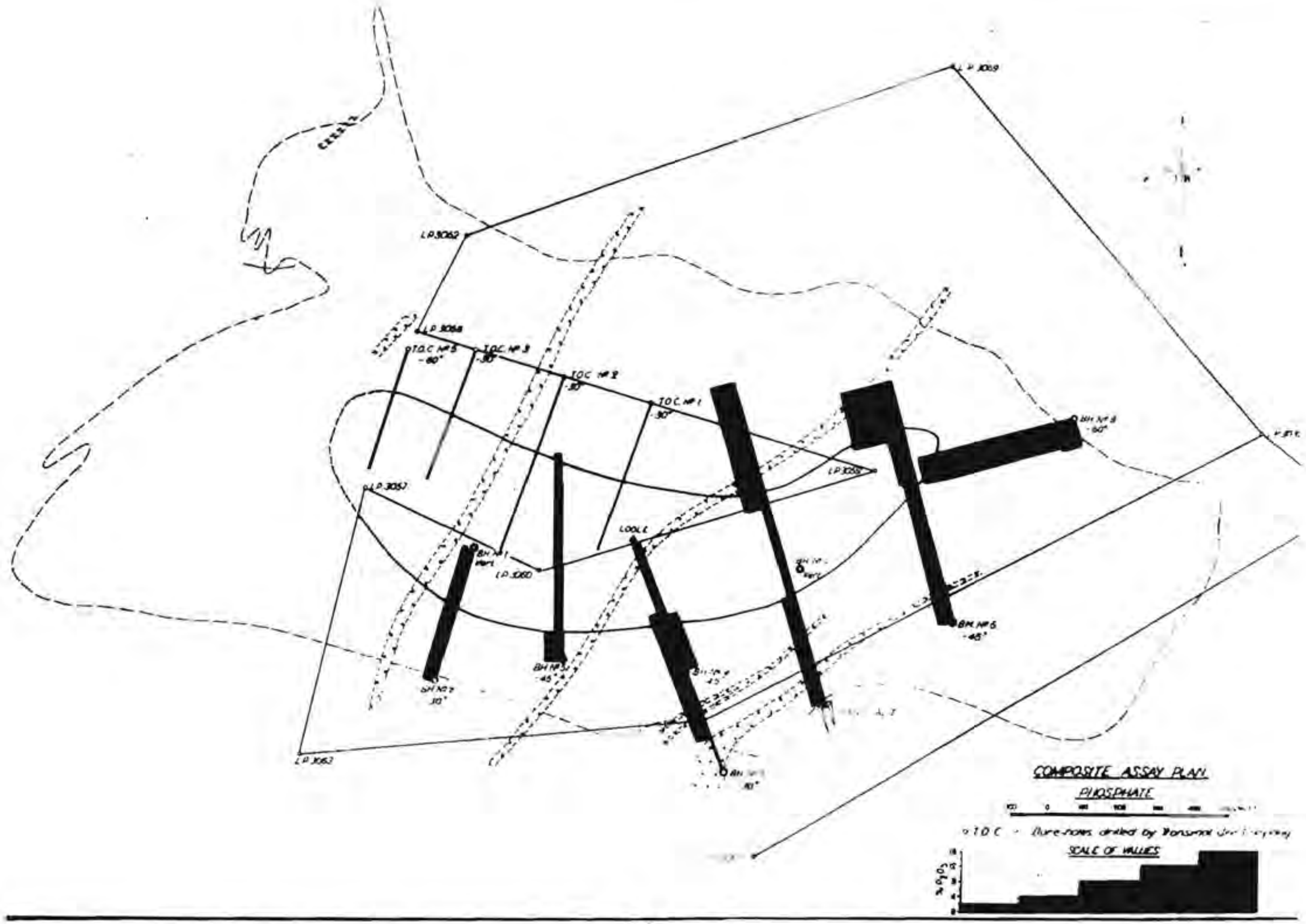
COMPOSITE ASSAY PLAN
PHOSPHATE
SCALE OF VALUES
L.P. 3069
L.P. 3062
L.P. 3058
T.O.C. Nº 5 -60°
T.O.C. Nº 3 -30°
T.O.C. Nº 2 -30°
T.O.C. Nº 1 -30°
L.P. 3057
L.P. 3060
L.P. 3055
L.P. 3063
BH Nº 1 Vert.
BH Nº 2 30°
BH Nº 3 -45°
BH Nº 6 -45°
BH Nº 8 -60°

Fig 24.

D. The Statistical Relationship

Detailed sampling was done to assess the economic potentialities of the carbonate member. Several thousand triple assays are available for phosphate, copper and uranothorianite in the form of P_2O_5 per cent, Cu per cent and e-U_3O_8 lbs per ton.

Using a large number of assays it is possible to compare the value distribution patterns of the minerals. This comparison should give useful confirmation in support of other geological facts bearing on the problem of the mode of origin of the carbonate member.

Comparing distribution patterns (Cousins 1956) consists in essence of the following procedure: The total number of samples assayed, are divided into value groups : e.g. 0 - 0.2, 0.21 -0.30 per cent etc. The total number of samples falling into each value group are added and expressed as percentages of the total. To find the cumulative frequency of occurrence of values, below each predetermined upper limit of a value group, the percentages are added progressively to give the cumulative frequency. The figures so obtained are plotted on special logarithmic probability graph paper - with the upper limit of value on the vertical and the cumulative frequency on the horizontal axes respectively.

In a normal distribution curve, the values are distributed symmetrically about the mean value. If plotted on a linear scale the curve is asymmetrical with a steep slope on the low value side of the mean value, and flatter on the high value side. The use of log probability paper permits the ordinary cumulative frequency curve to be plotted as a straight line.

Theoretically the pattern of distribution followed by all mineral deposits will fall on a straight line. This depends in practice on having an infinite number of samples in each value group. This condition cannot, however, be reached. As a result, the points will scatter especially for the highest value groups. To reduce this scatter, although values as high as 20.96 per cent P_2O_5, 19.96 per cent Cu and 12.1 lbs per ton e-U_3O_8 were obtained, no value groups were used where the number of samples were less than 30. Variations due to sampling may be assumed to have cancelled each other since triple assays were done on the same sample.

The cumulative frequencies obtained for predetermined value groups where the 'population' of samples is sufficient for statistical purposes are given in table V. These figures, based on approximately 1500 samples, have been plotted on log probability paper (fig. 25), to show the value distribution curves. Value groups above 1.0 are available for copper assays. These have, however, not been plotted as the results cannot be compared to corresponding value groups for equivalent uranium and phosphate.

The vertical position of the distribution curve determines the relative richness of the deposit in any of the constituents considered. Since, the minerals are present throughout the carbonate member in the following approximate proportions: P_2O_5 : Cu : e-U_3O_8 :: 15 : 5 : 1, value grouping was reduced by a factor of 10 in the case of P_2O_5 and increased by 20 in the case of e-U_3O_8, for ease of comparison.

From the value distribution patterns we find parallel straight lines for copper and equivalent uranium; indicating a similar pattern of distribution although, the minerals have varying mean values. If value groups for copper above 1.0 are plotted, the points fall below the straight line drawn for value groups less than 1.0. The difference of slope of the phosphate cumulative frequency curve indicates a different value distribution pattern for this constituent.

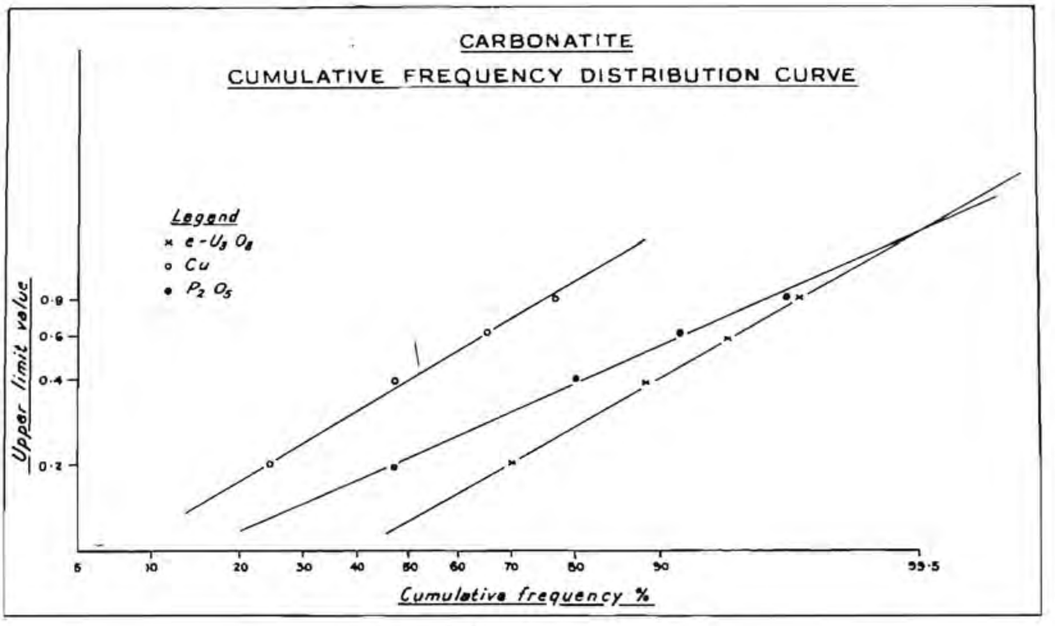

Fig. 25

The steeper slopes obtained for copper and equivalent uranium indicate that the spread from the mean value is wide for these constituents while the flatter phosphate curve suggests a narrower spread from the mean value.

On the basis of these results we may deduce that conditions favourable for the concentration of urano-thorianite and copper sulphides were the same or closely similar whereas, these conditions were unfavourable for apatite deposition. This indicates a proportional availability for copper and uranothorianite, but not apatite.

TABLE NO. V - THE STATISTICAL RELATIONSHIP OF COPPER, EQUIVALENT URANIUM AND PHOSPHATE

Value group	No. of samples	% of total	Cumulative frequency %
	Copper		
0 0.20	354	24.8	24.8
0.21 - 0.40	319	22.5	47.3
0.41 - 0.60	254	17.9	65.2
0.61 - 0.80	172	12.1	77.3
0.81 - 1.00	138	9.7	87.0
1.10 - 1.20	84	5.9	92.9
1.21 - 1.40	56	4.0	96.9
1.41 - 1.60	40	2.8	99.7
Totals	1417		
	Equivalent Uranium		
0 - 0.20	1030	70.6	70.6
0.21 - 0.40	262	18.0	88.6
0.41 - 0.60	87	6.0	94.6
0.61 - 0.80	44	3.0	97.6
0.81 - 1.00	35	2.4	100.0
Totals	1458		
	Phosphate		
0 - 0.20	727	48.2	48.2
0.21 - 0.40	485	32.1	80.3
0.41 - 0.60	187	12.4	92.7
0.61 - 0.80	71	4.7	97.4
0.81 - 1.00	39	2.6	100.0
Totals	1534		

E. - The Uranium : Thorium Ratio

Adams (Faul, 1954) has provided substantiation for earlier conclusions in the literature that the uranium : thorium ratio is fairly constant. Data on the ratio in the acid volcanics from the Lassen Volcanic National Park, California indicate no large shift in the ratio and show that thorium is about three times more abundant than uranium in unweathered volcanic rocks, i.e. those in which equilibrium is not disturbed. It is stated that the ratio probably remains constant during differentiation.

To establish the uranium : thorium ratio, three samples were submitted to the Government Metallurgical laboratory and to the United States Atomic Energy Commission for chemical analyses. The samples were portions of crushed core from bore-hole 1, taken at depths of 106, 113 and 198 feet respectively. In addition a cleaned sample of uranothorianite was submitted to the Division of Chemical Services. The results are tabulated in table VI. In the tabled figures there is fair agreement between the laboratories concerned; the ratios are fairly consistent and their average close to that obtained by the Division of Chemical Services.

Subsequent work on concentrates raised doubts as to the constancy of the ratio. A specially selected suite of samples was, therefore, submitted to the Government Metallurgical laboratory. These samples were selected from bore-cores and from the adit so that they represent a large part of the carbonate member. The results, given in table VII, suggest that the proportions of uranium and thorium in uranothorianite are quite variable.

If any relationship exists between uranium and thorium in uranothorianite it should emerge if a sufficient number of uranium and thorium assays, obtained by equilibrium methods[1] on the same sample, are grouped into equivalent uranium oxide groups of limited value range (e.g. 0.020 to 0.030 to 0.040 etc. e-U_3O_8 per cent) and calculating the mean uranium and thorium values falling within each value group. Although uranium and thorium values in excess of one per cent occur, the number of samples in each 0.010 equivalent uranium oxide per cent group above 0.1 were all less than thirty; consequently no figures are given for them. The results obtained are given in table VIII.

An alternative method, giving some idea of the variation of the ratio within each group, is to calculate a uranium-thorium ratio for each sample; to group these ratios and to calculate the percentage of samples within each equivalent uranium oxide group that falls into a series of ratio groups. The results obtained by this method are given in table IX.

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1. The determination of uranium and thorium, physically in the same ore by the equilibrium method[1] involves simultaneous measurement of the beta and gamma radiations emitted by the various decay products of the uranium and thorium series.

Table VIII shows the uranium : thorium ratio to remain fairly constant for increasing equivalent uranium oxide values. A mean value of 1 : 2.81 was obtained. This figure was obtained from analysis of 346 samples, segregated into value groups ranging from 0.020 to 0.1 per cent equivalent uranium oxide. The ratio for individual groups was found to vary from 2.47 to 3.13.

Table IX illustrates the spread of the ratios yielded by the individual samples within equivalent uranium oxide value groups. The table indicates that whereas the ratio is variable, 73 per cent of the samples considered have ratios falling between 1:1 and 1:3.

TABLE NO. VI

THE URANIUM : THORIUM RATIO AS INDICATED BY CHEMICAL ANALYSES

Sample	Physical Assay	Chemical Analyses U_3O_8	ThO_2	Ratio ThO_2/U_3O_8	Laboratory
1.	0.50	0.26	1.01	3.89	A.E.C.
		0.277	1.03	3.72	G.M.L.
	0.475				G.U.
2.	1.00	0.64	2.31	3.61	A.E.C.
		0.628	2.11	3.36	G.M.L.
	0.998				G.U.
3.	0.30	0.18	0.28	4.33	A.E.C.
		0.203	0.80	3.94	G.M.L.
	0.34				G.U.
4.		16.6	59.9	3.61	C.

A.E.C. United States, Atomic Energy Commission.
G.M.L. Government Metallurgical Laboratory, South Africa.
G.U. Geological Unit, Atomic Energy Board.
C. Chemical Services, Department of Agriculture.

Samples 1 to 3 are cores taken from vertical bore-hole No. 1 at the following depths: 107, 113 and 199 feet.
Sample 4 is a cleaned sample of uranothorianite.

TABLE NO. VII

THE URANIUM : THORIUM RATIO AS INDICATED BY CHEMICAL ANALYSES

Samples	Physical assay e-U_3O_8	Chemical Analyses U_3O_8	ThO_2	Ratio ThO_2/U_3O_8
1.	0.293	0.161	0.607	3.77
2	0.219	0.142	0.453	3.19
3	0.181	0.069	0.453	6.57
4	0.204	0.117	0.365	3.12
5	0.362	0.157	0.903	5.75
6	0.830	0.520	0.885	1.71
7	0.361	0.234	0.567	2.42
8	0.198	0.148	0.191	1.29
9	0.197	0.157	0.234	1.49
10	0.304	0.129	0.411	3.19
11	0.221	0.094	0.582	6.19
12	0.952	0.736	1.28	1.74

TABLE VIII

THE RELATION BETWEEN URANIUM AND THORIUM ACCORDING TO EQUIVALENT URANIUM OXIDE GROUPS

e-U_3O_8 % group	No. of samples	Mean values in per cent			ThO_2/U_3O_8
		e-U_3O_8	U_3O_8	ThO_2	
0.020 - 0.030	50	0.027	0.018	0.051	2.85
0.031 - 0.040	53	0.035	0.023	0.071	3.13
0.041 - 0.050	46	0.046	0.029	0.080	2.72
0.051 - 0.060	52	0.055	0.036	0.103	2.83
0.061 - 0.070	39	0.065	0.042	0.129	3.08
0.071 - 0.080	33	0.076	0.053	0.138	2.61
0.081 - 0.090	35	0.087	0.054	0.150	2.81
0.091 - 0.100	30	0.096	0.068	0.167	2.47
Total	346				
Mean ratio					2.81

TABLE IX

THE VARIATION OF THE URANIUM:THORIUM RATIO WITHIN EQUIVALENT URANIUM OXIDE GROUPS

e-U_3O_8 per cent group	Ratio Groups ThO_2/U_3O_8 *												No of samples
	0- -1.0	1.1- -2.0	2.1- -3.0	3.1- -4.0	4.1- 5.0	5.1- -6.0	6.1- -7.0	7.1- -8.0	8.1- -9.0	9.1- -10.0	11.1- -12.0	13.1- -14.0	
0.021-0.030	2.0	30.0	20.0	22.0	12.0	10.0	2.0	2.0	-	-	-	-	50
0.031-0.040	-	18.9	26.4	24.5	9.4	7.6	5.7	3.8	1.9	-	1.9	-	53
0.041-0.050	4.4	17.4	41.3	23.9	4.4	6.5	-	2.2	-	-	-	-	46
0.051-0.060	3.9	25.0	26.9	25.0	5.8	5.8	1.9	1.9	-	1.9	-	1.9	52
0.061-0.070	-	28.2	15.4	23.1	20.5	2.6	5.1	5.1	-	-	-	-	39
0.071-0.080	4.9	29.3	24.4	22.0	12.2	2.4	4.9	-	-	-	-	-	41
0.081-0.090	8.6	14.3	40.0	11.4	5.7	11.4	8.6	-	-	-	-	-	35
0.091-0.100	4.2	16.7	37.5	20.8	12.5	-	-	4.2	-	4.2	-	-	30
Total													346
Averages	3.5	22.5	29.0	21.6	10.3	5.8	3.5	2.4	0.2	0.8	0.2	0.2	

* Ratio groups 10.1 - 11.0 and 12.1 - 13.0 have been omitted from the above table as no values fall within them.

F. Conclusions

A sympathetic relationship exists between the copper and uranothorianite in that the higher grades of copper ore show higher radioactivity. The apatite on the other hand diminishes in content as copper grade increases. This relationship is not a close one but the same boundaries confine both the copper and uranothorianite.

It is possible to subdivide each inclined bore-hole and the adit into an 'inner' and 'outer' zone. The main concentrations of copper and uranothorianite occur in the 'inner' or central irregular zone. This zone is kidney-shaped and elongated in an east-west direction.

The distribution of phosphate values provides the clearest picture. The change from comparatively good to poor phosphate mineralization is clear-cut. The zone of good values passes into ground showing consistently low values relieved occasionally by areas of sporadic enrichment. Copper is distributed throughout the carbonate member but is best concentrated in the centre. Uranothorianite is closely confined to this part of the mass. The distribution shows occasional enrichment in the outer portions of the carbonate member, but not to the same extent as copper. The distribution of magnetite bears no relationship to either apatite, uranothorianite or copper.

The highest concentration of copper and uranothorianite is found where jointing and brecciation is prominent.

A vertical bore-hole drilled into the more strongly mineralized zone provided evidence of the continuation of mineralization throughout the total length of the borehole of 1893 feet.

Inclined drilling shows that the carbonate-phoscorite contact is sharp and that the carbonate member is probably a plug-like body the walls of which are practically vertical.

The pattern of mineralization can be expected to be vertically disposed and to follow at depth the distribution of radioactivity anomalies obtained at surface.

A statistical study of the distribution of apatite, copper and uranothorianite indicates that similar conditions were favourable for the concentration of copper and uranothorianite, but not apatite.

The results of chemical and radiometric analysis show that the proportion of uranium and thorium in uranothorianite varies. Thorium, however, always predominates over uranium. A statistical calculation gives a ratio of 1 : 2.81 as a fair approximation.

VI. - THE PARAGENESIS OF THE COMPLEX

A. General

In common with alkali complexes everywhere, the genesis of the rocks at Phalaborwa has been the subject of much controversy. The main points which lead to conflict are the relation of the syenite to the pyroxenite and that of the carbonate member to the pyroxenite.

Most of the differing conclusions are largely the result of incorrect mapping. This is not unexpected in an area where the surface geology is obscured by a thick cover of calcrete. Over a great portion of the complex information can only be obtained from artificial exposures made for prospecting purposes. With increasing economic interest focussed on hitherto neglected portions, such as the carbonate member, information has been obtained which allows a revision of earlier work.

The theories previously advanced to account for the carbonate member in explaining the geological history of the complex include a metamorphic origin, assimilation of limestone by a granitic magma, and a magmatic origin.

There is no fundamental reason to distinguish between metamorphism or assimilation of limestone which has taken place <u>in situ</u>. While the exponents of both theories agree that the syenite has been formed as the result of interaction between granite magma and limestone, the origin of the pyroxenite forms the basic difference between the two ideas. Consequently the pyroxenite - carbonate contact zone is of fundamental support to either theory in that both stand or fall by virtue of this relationship.

Shand, the leading exponent of the assimilation theory, has applied a variant of Daly's hypotheses to explain the origin of the rocks at Phalaborwa. He pictures "a front of 'granitic' magma advancing into the limestone reacting with it, and precipitating diopside as it advanced" (reply to discussion, Trans. Geol. Soc. S. Afr., LI, 1948). Since this possible assimilation apparently took place in situ and without complete digestion of the limestone, it is obvious that the phenomena observed at the carbonate contact should be the same irrespective of whether metamorphism or assimilation was the dominant process. This contention is supported by Shand's statement that his work is not irreconcilable with the metamorphic theory of du Toit. He regards the two ideas as supplementary and not contradictory (reply to discussion, Trans. Geol. Soc. S. Afr., 34, 1931).

The two theories can best be discussed together under the heading 'a limestone syntectic origin', in the sense that the term syntexis includes both the metamorphism and assimilation of foreign matter.

B. A Possible Limestone Syntectic Origin

The leading exponents of the limestone syntectic theory are du Toit, (1931), Shand (1931) and Gevers (1948). Their ideas have been summed up by Shand (1949) as follows:-

"The intrusion of granite into the ancient schists of this region took place in several stages. The products of reaction with moderately magnesian limestone are:-

a. diopside-arfvedsonite syenites, containing microcline and only a little quartz;

b. shonkinites (melanocratic syenites) consisting roughly of one third microcline, two thirds diopside with some apatite;

c. pyroxenites, almost wholly composed of diopside or diopside and apatite; also apatite rocks".

Shand (1949) has made the following statements:-

"All these rocks are cut by younger granite. In the limestones, however, no granite veins were observed, but only veins of syenite and shonkinite". (pg. 82)

"The central limestone mass which has been charged with magnetite and apatite has also developed diopside and olivine by thermal metamorphism". (pg. 84)

There is no evidence, whatsoever, of younger granite cutting the pyroxenite nor veins of syenite or shonkinite in the carbonate member. Furthermore no diopside is developed in the carbonate member and it thus becomes necessary to have a closer look at the basic principles of metamorphism of limestone by granite.

Exponents of the syntectic theory, have in suggesting a sedimentary origin for the carbonate member, been forced to indicate a possible source for an isolated body of sedimentary limestone enveloped in a 'sea' of granite of such original dimensions that a large remnant still exists. Most supporters have suggested a block of dolomite belonging to the Transvaal System, while du Toit and Gevers favour the carbonate rocks of the Murchison Range.

The original chemical composition of dolomite is of basic importance in any explanation favouring assimilation or metamorphism by an acidic magma.

Du Toit (1954) gives the following analysis of dolomite:-

$CaCO_3$	....	48.4%
$MgCO_3$	....	40.6%
$FeCO_3$	....	1.8%
$MnCO_3$	....	2.9%
SiO_2	....	5.2%

The carbonate rocks of the Murchison Range have been described by Hall (1912, Mem. 6) as dolomite and ankeritic or in other words magnesian-calcium-iron carbonates.

It is known that when dolomite is metamorphosed silica shows an affinity for magnesium in the presence of calcium and that lime tends to unite with the foreign material in the dolomite with the liberation of CO_2. Assuming that the syntectic theory is applicable and that the complex was formed as the result of interaction between an acid magma and dolomite the products of metamorphism will depend on the proportion of silica available. The reaction will proceed according to the following equations:-

$$\underset{\text{dolomite}}{3CaMg(CO_3)2} + 4SiO_2 = \underset{\text{tremolite}}{CaO,3MgO,4SiO_2} + 2CaCO_3 + 4CO_2$$

$$CaMg(CO_3)_2 + 2SiO_2 = \underset{\text{diopside}}{CaMg(SiO_3)2} + 2CO_2$$

$$2CaMg(CO_3)_2 + SiO_2 = 2CaCO_3 + \underset{\text{olivine}}{Mg_2SiO_4} + 2CO_2$$

The carbonate member (table II) contains less than 2.3% SiO_2 so that the total absence of tremolite is not unexpected. Although Brandt (1948) mentions diopside in the carbonate, the writer was unable to find any. The scarcity of diopside in the carbonate is confirmed by the investigations of du Toit and Shand (reply to discussion, Trans. Geol. Soc. S. Afr., 1948). Magnesian silicate is present as olivine and chondrodite and the tenets of metamorphism are thus not opposed by the basic chemistry on the marble side of the process. It is not clear, however, how diopside would form on such a large scale as a metamorphic product in the pyroxenite and yet not at the carbonate contact.

The rocks most congenial to the formation of contact metasomatic mineral deposits are limestone and dolomite. Metamorphism will of necessity give rise to great quantities of CO_2, escape of which will bring about a relief of pressure in the invading magma in the direction of the dolomite. This would allow the transportation of the gaseous constituents in the direction of relief of pressure. As a result, intense contact metasomatism would be expected in addition to the normal heat effects, such as the recrystallization of the calcite without considerable change in chemical composition. This metasomatism would be manifested by marked changes in the periphery of the dolomite with far less pronounced effects in the 'front' of the invading magma.

It is reasonable to assume that the resulting metamorphic aureole would be characterised by a gradational passage from granite through a zone of intense metasomatism to normal dolomite, with the extent of the metasomatism being dependent on the temperature of the invading magma and the proportions of the dolomite originally available.

The fact that no metamorphic aureole exists in the carbonate and that the phoscorite is in sharp contact with the former does not make a syntectic origin sound very plausible. The sharp contact proves that the carbonate arrived in its present position in the same way as any intrusive would have done. Furthermore, the spatial distribution of apatite, uranothorianite and copper sulphides in the carbonate member is suggestive of a magmatic origin.

The mineral assemblage in the carbonate member does not offer conclusive support to the syntectic theory. The minerals present which are characteristic of contact metasomatic deposits are:- olivine, chondrodite, the micas and fluorite; the metallic oxides of iron and titanium and the common base mineral sulphides, chalcopyrite, bornite, pyrite and pyrrhotite. The mineralogical evidence shows that pyrite is secondary, after magnetite. The others, however, are also all common in high temperature deposits with magmatic affiliations.

Brandt (1948) has raised the following additional objections to the metamorphic explanation:-

1. The rocks of the complex intruded the Archaean granite on a large scale but fragments of carbonate are not found in the breccias and sills and dykes of the younger peralkaline granite.

2. Isolated syenites intrusive into roots of the Primitive System, in which there is no secondary carbonate, occur in the vicinity of the Olifants river. The absence of fragments of carbonates in the breccias of these syenites tend to show that the magma was not in contact with carbonate of sedimentary origin.

3. Limestone is susceptible to any changes and easily looses its individual character when an igneous rock intrudes it. In this case the structure of the igneous rock will be reflected in the limestone. The map of the Murchison Range (S. Afr. Geol. Surv.) shows clearly the property of adjustment of the limestone in this area. They are drawn-out into long lenses showing a strong tendency to be elongated parallel to the flow structure of the granite gneiss. On comparison with the form of the carbonate member, a striking difference can be seen.

Gevers an exponent of a metamorphic origin (reply to discussion, Trans. Geol. Soc. S. Afr., LI, 1948) has stated that "should it be proved that the entire limestone body, together with its outer fringe of serpentine-magnetite-apatite rocks, possesses transgressive contacts with reference to the pyroxenite, then of course du Toit's hypotheses favoured by me will fall away". This statement is equally applicable to partial assimilation of limestone, _in situ_, by a granitic magma.

Detailed mapping and the results of prospecting show that the serpentine-magnetite-apatite body (i.e. the phoscorite) is a separate entity containing inclusions of pyroxenite and forming sharp contacts with both the pyroxenite phase and carbonate. On this basis we must conclude that the carbonate member is intrusive.

C. A Suggested Magmatic Origin for the Carbonate Member.

That the carbonate member is of magmatic origin was first suggested by Brandt (1948). His idea that Loolo Kop represents a volcanic conduit differs radically from those of earlier investigators.

Brandt has visualized a basic magma differentiating in depth into a basic or pyroxenitic fraction, a syenitic fraction, a carbonate fraction and a silica and sulphide fraction. He is of the opinion that the pyroxenite was emplaced first and after consolidation was intruded by syenite. Lastly, the intrusion of the carbonate member carrying the iron and copper ores took place. The widespread distribution of biotite, apatite, phlogopite, vermiculite, chlorite and serpentine in the pyroxenite is attributed to a pnuematolytic phase of the syenite magma flooding the pyroxenite with acid end-stage members. The intrusion of the syenitic magma is regarded as only slightly later than this pnuematolytic stage.

In tabulated form the processes resulting from or associated with the syenite intrusion, held responsible for the mineralization of the complex by Brandt, are:-

a. Intrusion of the olivine-pyroxenite fraction;
b. pnuematolytic action characterised by serpentinisation, and carbonitisation of the basic fraction accompanied by the formation of phosphate, phlogopite and magnetite which preceded the syenite intrusion;
c. syenite intrusion and the formation of syenitic pegmatite;
d. further carbonitisation together with silicification and hydration of phlogopite which was changed to vermiculite. This final stage taking place at an advanced period of the syenite intrusion when a renewal of mineralization, accompanied by brecciation, caused the percipitation of carbonate with iron and copper.

Brandt has deduced the order of intrusion, pyroxenite, syenite and carbonate, from the structural relations as observed by him. As this bears directly on the processes of mineralization it is necessary that his evidence be considered in greater detail.

As a preliminary step it would be of advantage to set out the information which has been obtained since Brandt's fieldwork was done. The following facts can be taken as conclusively established:-

1. The contact between the phoscorite and the surrounding pegmatitic rocks is sharp and inclusions of pyroxenite occur therein.

2. The carbonate member contains inclusions of phoscorite in its peripheral portion. Its contact with the phoscorite is sharp.

3. Drilling has proved that the carbonate member extends vertically at least to 1893 feet, the bottom of the deepest bore-hole. There is nothing to indicate that it will not continue to greater depths.

4. Veins of carbonate cut all the other rock types including granite.

5. A study of the distribution of apatite points to its maximum concentration in the phoscorite. In general the outer portion of the carbonate member shows a decrease in phosphate content when compared with the phoscorite, while a negligible concentration occurs in the centre.

6. A notable difference in titanium content of magnetite in the phoscorite and the magnetite in the carbonate member has been established spectrographically and chemically.

7. Diopside decreases in concentration from pyroxenite to phoscorite. In the carbonate member it is absent.

8. The mineragraphic, statistical and other evidence suggest that:-

   a. Uranothorianite and copper mineralization represent a late crystallisation at high temperature;

   b. they are genetically connected;

   c. there are two stages of mineralization, one directly associated with the emplacement of the carbonate member, and the second represented by a late emplacement along planes of weakness after partial or complete crystallisation.

According to Brandt the intrusion of the syenitic magma took place as repeated injections over a long period of time. These injections were, in order of age, as follows:-

a. A passive infiltration of peralkaline granite and syenite along joints in the Archaean granite.
b. A violent intrusion of the main syenite mass which gave rise to the tor-shaped hills (pl. II) and the associated brecciation.
c. The third period, again one of passive infiltration, taking place along cooling cracks in the earlier formed syenite.

The writer has no critisism to offer to the suggested manner of intrusion of the syenite. There are, however, several reasons for objecting to the suggested order of intrusion of the successive phases of the magma, and the conclusion that the mineralization of the complex is related directly to the emplacement of the syenite fraction.

It is now generally agreed that the complex was intruded into Archaean granite and that igneous activity in the area was terminated by the intrusion of dolerite dykes of Karroo age. These dykes are in no way connected to the igneous cycle which resulted in the emplacement of the complex.

The position on the syenite-shonkinite contact is not all clear. The whole problem of the time of intrusion of the syenite in relation to the other intrusive phases of the complex is related to the field and chemical relations of the shonkinite. The exponents of the syntectic theory, and Brandt, have brought much chemical evidence in support of their views. There is, however, very little experimental evidence on the chemical aspects and the ideas advanced are to a large extent speculative. The chemical approach can equally well explain the shonkinite as metasomatism of the syenite by the pyroxenite or alternatively as replacement of pyroxenite by syenite. The writer is thus of the opinion that more credence should be placed on the field relationships and spatial distribution of the rock members exposed at the present erosion level, than on speculative explanations based largely on laboratory chemistry.

In discussing the relationship of the shonkinite to the syenite and pyroxenite, Gevers wrote (1948), "There is no gradational transition between the pyroxenite and surrounding syenites and granite. Everywhere the contacts are intrusive in nature. Xenoliths of pyroxenites in various stages of assimilation are abundant in syenites, quartz-syenites and 'per-alkaline' granites and usually the latter rocks near the contacts are highly diopsidic, a belt of assimilation sometimes dozens of yards wide being very common". Gevers has concluded that the shonkinite is merely felspathised pyroxenite, a view with which Brandt agrees and whose evidence can be summed up as follows:-

1. Veins of microcline cut the pyroxenite;
2. along the contact the pyroxenite is highly felspathic in a zone up to 50 feet wide;
3. towards the centre of the pyroxenite the felspar decreases rapidly with a corresponding increase of mica and apatite;
4. pegmatitic syenites containing large xenoliths of pyroxenite are observed;
5. east and south-east of Loole Kop syenites penetrate

the pyroxenite and possibly connect with the tongue of syenite which occurs on the western side, south of Loole Kop.

Russell (1954), although remaining silent on the syenite problem, has described the syenite-shonkinite contact as, "usually gradational over a distance of a few yards, but is occasionally fairly sharp; it is almost vertically disposed. At many places irregular veinlets of potash-rich felspar occur in the shonkinite near the contact. The syenite adjacent to the shonkinite is extremely coarse-grained and in places pegmatitic".

The following objections to the suggestion that the field relations of the shonkinite support the emplacement of the pyroxenite as the initial fraction can be raised:-

a. There is no field evidence that syenite dykes and related pegmatites cut the pyroxenite nor the shonkinite or carbonate member. A fact which is not easily explained when the explosive nature of the main syenite intrusion is considered, particularly as related syenite sills and dykes have intruded the granite on a large scale.

b. The shonkinite is developed practically along the entire periphery of the pyroxenite. This is particularly marked where the rocks in contact with the shonkinite are syenite, but over fairly extensive areas the shonkinite is in contact with Archaean granite (fig. 1). The syenite cannot be held responsible for the development of felspathised pyroxenite where the latter abuts against granite. That the granite was already cooled and consolidated when the complex was intruded is suggested by the brecciated nature of the granite-syenite contact.

c. If Brandt's interpretation of the syenite-pyroxenite contact phenomena is correct, the position the syenite occupies around the periphery of the complex and that of later phases of intrusion (i.e. the phoscorite and carbonate member) in the centre of the complex requires a great deal of explanation.

d. At first sight the occurrence of irregular veinlets of potash-rich felspar in the shonkinite near the contact or veins of microcline in the pyroxenite, appear to be irrefutable evidence in favour of felspathisation of pyroxenite by syenite. It is, however, not unusual for a certain set of natural phenomena to be given widely different interpretations. As the veins are seen only in one plane the interpretation of their intrusive nature is difficult. In the writer's opinion while some of these veinlets appear to be intrusive into the pyroxenite in just as many instances they suggest exactly the opposite. They may represent assimilation of syenite by pyroxenite during remelting of the former and subsequent differentiation. The same explanation can be applied to apparent xenoliths of pyroxenite in syenite.

e. The description of a 'tongue' of syenite pre-supposes the intrusion of the syenite into the pyroxenite. Mapping (fig. 1) shows that this supposed tongue is actually composed of granite into which syenite is intrusive. The writer did not find any syenite penetrating the pyroxenite south and south-west of Loole Kop. Over this entire section shonkinite is present between these rock types.

The existence of numerous carbonate veins of almost similar mineral assemblage and arranged radially with respect to the carbonate member is of fundamental support in favour of a magmatic origin for the latter. Brandt's[1] descriptions of these veins and their relation to the complex are of interest.

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1. Translated from the original Afrikaans by the writer.

"Younger veins of silica and carbonate cut the older carbonate and serpentine rocks of which Loole Kop is made up. These veins are of several types. On the contacts they are fine-grained and branch along horizontal joints. In the veins thin streaks of magnetite are arranged parallel to the contacts and copper staining is present. Similar carbonate veins criss-cross the main body of carbonate in a prospect on the south-eastern slope of the hill, just above the shaft situated near the pyroxenite-marble contact. Brecciation sometimes took place along these veins, but also along joints in an irregular way as is shown by the many formless bodies of silica in the marble. The details point to the fact that the copper mineralization took place during this late period of carbonatisation and brecciation. It is also clear that the carbonate intrusion took place after serpentinisation".

Brandt's failure to distinguish the phoscorite as a primary rock type makes his description of little value. He refers to it as follows:- "In contact with the main body of marble a halfmoon subdivision of the marble, with iron and phosphate, occurs. Following this, south-west and west, there is a zone rich in biotite-vermiculite". Brandt states further, that exceptional serpentinisation, around the marble, is a notable characteristic of the rocks in this vicinity. Also that copper mineralization took place in the marble close to and in the silicified carbonatitic-serpentine.

These statements are incorrect on several points. At no place is the main mass of carbonate in contact with pyroxenite. The shaft referred to is sunk in phoscorite. There is no evidence, as observed in core from bore-holes and underground prospecting, that younger carbonate veins cut the main mass. His statement that copper mineralization took place in the marginal serpentinised portion of the carbonate member is, judging by the distribution thereof, obviously incorrect.

Without the realization of the true relationship of the phoscorite to the pyroxenite and carbonate member it is not surprising that Brandt seems unconvinced of the correctness of his argument. In support he mentions the work of Spurr (1923) and von Eckermann (1938) that carbonate can be expected in the late magmatic phases of basic magmas as the result of a reversal of the normal order of crystallisation; also Shand's (1947) conclusion that a deep-seated gabbroic magma can leave a residue rich in ferro-iron and that, during hydration, oxidation is automatic with the release of water vapour and the formation of magnetite. Brandt compromises in a footnote to the effect that von Eckermann's conclusion is based on insufficient evidence and that Shand's is more in keeping with the established ideas of a sedimentary origin for the Loole Kop marble with mobilisation thereof.

Then again he comments "The metamorphic origin as propounded by A.L. du Toit is certainly a feasible one, but requires readjustment in the light of new evidence. (Trans. Geol. Soc. S. Afr., LI, reply to discussion).

The writer disagrees, on the basis of the above arguments, that the pyroxenite was the first phase to be emplaced and that the shonkinite represents pyroxenite felspathised by the syenite. Nor is the mineralization of the complex connected with the syenite intrusion.

The mineralization of the pyroxenite is not the type which would be expected to result from a syenite cause. The gradational contacts of localised areas of concentration of apatite and vermiculite and the virtual absence of free iron; the overall increase of silica towards the centre of this body; the change to pegmatitic types with increasing distance from the syenite and the sharp contact of the pyroxenite phase with the phoscorite are more in keeping with normal crystalline differentiation after emplacement.

The suggestion is offered that the pegmatitic phases in the pyroxenite, which include the vermiculite deposits, are most likely the result of normal differentiation of the pyroxenite after emplacement, into members showing an increase of silica as differentiation proceeded, the various differentiates being characterised by gradational contacts with each other.

The elements making up the predominant mineral assemblage in both the phoscorite and carbonate member must all have been original constituents of the primary magma. They most probably became concentrated in these fractions by the process of differentiation.

The applicability of Holmes' ideas on the petrogenesis of alkali rocks, to the Palabora complex, as suggested by Russell, remains for consideration.

Holmes and Harwood have been responsible for several hypotheses advanced to explain the paragenesis of the alkali rock suites in Uganda. One of these, suggested in 1932, is that the rocks of the Tora-Ankola field resulted from the crystal differentiation of a primary peridotite magma under conditions of high pressure. This theory was discarded in 1936, in favour of the suggestion that the felspathoid rocks of the Bufumbira volcanic area represent "the 'undersaturated' end-products of syntexis between pre-existing sialic rocks (including granite) and highly energised alkali-rich emanations, the latter being the desilicating agent".

Holmes (1950) has reversed the limestone syntectic theory to explain the paragenesis of katungite from the volcanic field near Ruwenzori on the lines that magmatic carbonatite, presumably derived from the substratum, ascended into the sialic layer where it reacted with granite to form the rocks of the olivine-biotite-pyroxene series. Granite is regarded as the source of all the alk-aluminous material, Al_2O_3, SiO_2 and K_2O with Ga, Rb, Ba and Zr. It is suggested that the cafemic material, MgO, CaO, iron oxides, TiO_2 and P_2O_5 with Cr and Ni, came from the magmatic carbonatite.

Holmes (1950) in proposing the interaction of carbonatitic magma with granite of the sialic layer, has stated that the 'combination of high potash with cafemic constituents is the geochemical peculiarity which especially challenges explanation'.

The felspar of the granite in the Phalaborwa region is generally microcline - a potash variety containing up to 5 percent K_2O. (Shand 1931). Since any magma derived from the substratum, on passing through the granitic shell of the earth, may have done a great deal of assimilation it is obvious that the granite can be regarded as the source of the potash in the syenites.

It can, nevertheless, be argued that complete assimilation of limestone, of suitable composition, by high temperature granite and relocation of the constituents can also account for the high potash content.

Daly's theory of limestone assimilation by basaltic or granitic magma is still the subject of active discussion. The modus operandi required for the limestone syntectic theory is as follows:-

1. Solution of limestone by magma with the formation of felspathoids by desilication at the expense of potential felspar.
2. Fractionation in response to gravity resulting in sinking of heavy lime silicates and rise of lighter alkaline fractions.
3. Formation and rise of alkaline carbonates to the upper portions of the magma chamber where silica is substituted for carbon dioxide (Wahlstrom 1950).

Much critisism has been levelled at Daly's theory as the result of many investigations of alkaline complexes made during recent years. From these investigations it seems probable that, whether or not carbonatites are exposed at surface, they are the result of closely similar conditions.

In many of these complexes an easily available source of carbonate does not exist. Where it is readily available the carbonate rocks are generally of inadequate composition. To satisfy the geochemical relations the rocks which must be assimilated have to be a mixture of dolomite, siderite and magnesite with TiO_2, H_2O and P_2O_5 and notable amounts of other minor ingredients (Holmes, 1950).

Neither at Ruwenzori (Holmes, 1950) or at Phalaborwa is there any evidence to suggest that a granitic magma was available to assimilate carbonate rocks. Nor is primary peridotite or the material of the substratum an adequate source of potash.

Higazy (1954), on the basis of the trace element contents of the different volcanic ultrabasic potassic rocks of Southwestern Uganda and the Belgian Congo, provides convincing support of the petrogenetic evidence of Holmes. He regards a basaltic parentage for these rocks as practically impossible since they are ultrabasic and potassic and enriched in Cr, Rb, Sr, and Zr, elements which are normally absent in basaltic rock and sedimentary limestones. Sr and Zr abundance is also a feature of the carbonate member at Phalaborwa. Furthermore, basaltic magmas normally differentiate into residues with increasing silica as differentiation proceeds.

With reference to the first point of Daly's hypotheses Turner and Verhoogen (1951) concluded:-

"There is no conclusive experimental evidence on this subject. Several cases have been recorded where nepheline syenites appear to have formed as local variants of granite in the vicinity of limestone. But in view of the widespread distribution of both granites and limestone and of the great interest aroused amongst geologists by the speculations of Daly and Shand, much more numerous instances would be expected if this were a normal petrogenic process".

It is not intended to suggest that granitic magma does not suffer desilication by reaction with limestone, but merely that it did not take place at Phalaborwa. It is extremely doubtful if complete assimilation followed by differentiation would give rise to a magnesian carbonate rock but rather a hybrid type.

Theoretically the reaction between granitic rocks and 'magmatic carbonatite' as such offers a possible explanation of the geochemical relations at Phalaborwa. Here the unusually high potash content of the syenite (15.9% K_2O, Shand, 1931) and the high potassium-sodium ratio in the pyroxenite can have resulted from such interaction.

The acceptance of a carbonatitic magma, actually the reversal of Daly's limestone assimilation theory, does not, however, provide any explanation of the differentiation process involved at depth, separate emplacement of the various fractions and the concentration of copper sulphides, uranothorianite and other elements of original volatile nature in the carbonate member. All that this concept accomplishes is to provide a secondary magma which has, as the result of assimilation of granite, gained in composition the elements, notably silica and potash, required to account for the rock-types exposed at Phalaborwa. The problem of the differentiation of the magma into members showing an increase of basicity towards the centre and the characteristic accessory mineral assemblage in the carbonate member remains unsolved.

The process of differentiation in a magma by gravitational crystallization, regarded by many authorities to be the prime cause of differentiation, proceeds as follows:-

The first solids to form are generally the heavy basic minerals such as magnetite, which depletes the residual liquid portion in the elements which go to form the earlier crystals. This heavier fraction sinks in the lighter liquid magma until eventually all the earlier-formed minerals have settled out and the residual magma remains above. If the earlier-formed minerals are lighter than the remaining elements, as in certain basic magmas, they would rise to the top, giving a similar separation of liquid and solid. In some basic magmas the order of crystallisation is reversed; basic felspar may be the first to crystallize and iron become concentrated in the residual magma. (Bateman 1955).

Barth (1954) has provided an explanation for the subvolcanic igneous rocks of the Oslo region as the result of degassing of the earth, which appears to offer a possible explanation of the processes necessary to account for the Phalaborwa suite.

Barth wrote, "Thus the Permian Oslo graben represented an active zone of degassing. Energised hot vapours from below moved upwards, fumed and fused the pre-existing rocks. By partial refusion a liquid portion of syenitic-granitic composition was formed; orogenic movements did not interfere, the liquid therefore percolated upward on its own accord, leaving behind a more basic residue, and as it did so, itself differentiating under the influence of gravity. Thus a vertical differentiation in the whole prism was effected. More energy and more vapour rich in alkalies enhanced the differentiation and produced from the pre-existing crystalline rocks large volumes of granitic-syenitic-monzonite magmas filling the upper parts of the prism, whereas the lower levels of the prism were filled by basaltic magmas originated by syntexis of the solid residue and the primary basaltic material of these levels. Thus the Oslo magmas were born <u>in situ</u> freed from any filial bondage to a basaltic mother magma".

The rocks making up the Oslo province are described as syenodiorite, syenite and granite containing abundant felspars and insignificant amounts of pyroxene, hornblende and biotite. They are regarded by Barth as representing the top part of the original magma chamber. The rocks are thus similar to the syenite phase at Phalaborwa.

The mechanism required to account for the separate emplacement of the various fractions of differentiation is that the magma, from which the various fractions differentiated, possessed a marked energy surplus, and that the fractions gained this energy in the form of ascending energy rich emanations after differentiation, and were thus able to move into their present position because of this surplus.

The Palabora Complex is, comparatively, of very small dimensions and it is possible that the rocks comprise all the components of the completoly differentiated magma chamber. On these lines the syenite represents the upper portion of the original magma chamber; the pyroxenite and phoscorite the more basic lower portion while the carbonate member represents the residual primary magma possessing a great deal of surplus energy.

The contention that the high concentration of alkalies, titanium, fluorine, phosphorous and zirconium in the Oslo suite were already present in the pre-existing crust and were not supplied by juvenile emanations is not in accord with the evidence at Phalaborwa. Here it seems as if potash and Al_2O_3, as suggested by Holmes, were the main constituents derived from the crustal rocks and that the majority of the rare elements were original constituents of possible alkali-rich emanations. Furthermore, the evidence at Phalaborwa shows that an independant <u>mise-en-</u>

place of the different members took place. Barth's suggestion does, however, provide a feasible explanation of the modus operandi required to arrange the various differentiates in the magma reservoir in the order of eventual emplacement.

Bassett (1954) has offered a third explanation. He suggests that the universal association of carbonate rocks and nepheline syenite result from the separation of an undersaturated magma of nepheline-syenitic composition with water and carbonic acid into two liquid phases. The slightly denser carbonate one settling out and leaving a more acidic syenitic magma above. Both these phases eventually solidified. Volcanic activity was preceded by the mobilization of the syenite and carbonatite. The concentration of the characteristic accessory minerals is explained as the result of their greater solubility in the carbonatite than in the syenite. The rocks at Phalaborwa cannot be accounted for as the derivatives of a nepheline-rich syenite magma. It is unlikely that separation of such a magma would give rise to the comparatively large volume of pyroxenite.

The ideas of both Holmes and Barth are based equally on hypothetical assumptions; conjuring tricks according to Shand (1945). It seems clear, however, that assimilation of crustal rocks did take place under the influence of either carbonatitic magma or alkali-rich emanations and solutions derived from the primary magma. Which of the two was the most probable remains uncertain. Perhaps both agencies were equally active. In this connection Pecora (1956) suggests that in the formation of carbonatites, gases were the most active and that gas transfer could contribute significantly to their formation.

The rock types at Phalaborwa vary from potash-aluminium silicates through calcium-magnesium silicates to magnesium-calcium carbonates. No doubt a close genetic relationship exists, and the evidence suggests that a primary alkalic magma, after possible enrichment by assimilation of granitic rocks differentiated at depth. Four distinct phases of differentiation and emplacement, as indicated by the sharp contacts, appear to have been involved. The magmatic fractions must have been discharged intermittently from the magma reservoir. The syenite was evidently emplaced first, and was followed by the pyroxenite and in turn by the phoscorite. Titanium and phosphorous reached their maximum concentration in the phoscorite fraction. The phoscorite was followed by the intrusion of the carbonatite into already consolidated phoscorite.

That the carbonatite is the youngest member is supported by Larsen and Phair's (Faul, 1954) generalization that the maximum concentration of uranium and thorium is found in the youngest member of a series, regardless of the particular liquid line of descent that the magma may have followed.

The writer is not in agreement with the suggestion (Brandt, 1948) that the emplacement of the carbonatite was passive and in the nature of magmatic stoping of rocks. Although pyroxenite rich in magnesium is wellknown to be highly susceptible to the action of carbonate rich solutions, the obviously brecciated nature of the phoscorite shows that the carbonate emplacement was of a forceful type.

As has already been suggested the pyroxenite underwent further differentiation, after arriving in its present position, into members showing an increase of silica as differentiation proceeded.

The concentration of magnetite, sulphides and rare elements in the carbonatite, needs some explanation. The fact that iron was continuously withdrawn from the magma reservoir follows from its widespread distribution in the phoscorite and carbonatite. In the pyroxenite stage the tendency for iron to form silicates was sufficiently strong to absorb all the iron as ferro-magnesian silicates. With the continued withdrawal of iron, accompanied by titanium which crystallized with the phoscorite, the residual magma eventually became deficient in the latter element. It is inferred that much iron remained in the residual more carbonatitic magma and finally separated out at a late stage of consolidation. With progressing crystallization there would be an increasing concentration of the volatiles in the diminishing residual liquid; the abundance of phlogopite indicating a high concentration of the hydroxyl molecule in the volatile fraction. These volatiles tended to act as mineralizers.

The copper and the rare elements such as uranium, thorium, nickel and zirconium appear to have become concentrated during the process of differentiation in residual liquors by the mineralizers, which also carried large quantities of iron.

Pecora considers that the necessary carbon dioxide for carbonatite formation is derived by a process of concentration of residual ingredients during crystallization of the silicate minerals. The minor, but characteristic constituents, become concentrated during the silicate crystallization.

Beyschlag (1914), has stated that the solubility of sulphides is much greater in basic silicates, those rich in FeO, MnO and CaO, than in those which are acid. It follows, that as differentiation proceeded with decreasing content of silica there was a rapid increase in the amount of sulphide in the residual melt. The widespread distribution of these elements in the carbonatite suggests that the carbonate-rich fraction was able to take up and carry along some, but not all the copper and rare elements. This portion eventually crystallized with the carbonatite core.

If high temperatures are maintained long enough, silica free mineral associations appear; the volatiles become concentrated and may cause shattering of the already consolidated roof (Backlund, 1932). The mineralogical evidence suggests that the bulk of the sulphides were introduced at temperatures in excess of 600°C. Distribution diagrams show that they are best concentrated in a nearly central zone characterised by shattering and brecciation. It follows that the activity was terminated by the deposition of copper, uranium and thorium from a strongly charged gaseous phase in solidified carbonatite, causing enrichment of these elements.

D. Conclusions

The paragenesis of the Complex has in the past been explained as metamorphism of, or assimilation of limestone. These ideas are fundamentally the same as the origin of the pyroxenite is the basic difference. An explanation based on the above theories is untenable.

That the carbonate member is of magmatic origin, was first suggested by Brandt who deduced the order of intrusion of the Complex to be pyroxenite, syenite and carbonate. He concluded that the mineralization is related directly to the emplacement of the syenite fraction. In the light of new information it is considered that neither the order of emplacement nor the cause of the mineralization as suggested by Brandt is correct.

The mineralization of the pyroxenite is more in keeping with normal crystalline differentiation after emplacement. The various differentiates in this suite are characterised by gradational contacts with each other.

It is considered that the elements in the phoscorite and the carbonate member were all original constituents of the primary alkalic magma which became concentrated in these fractions by differentiation processes.

The interaction of carbonatitic magma with granite of the sialic layer offers an explanation of the geochemical relations at Phalaborwa, but Barth's idea that degassing of the earth results in fusion of pre-existing crustal rocks and effects a vertical differentiation in the magma reservoir seems more applicable to Phalaborwa.

It is probable that assimilation of crustal rocks took place under the influence of either carbonatitic magma or alkali-rich emanations and solutions derived from the primary magma. The evidence suggests that a primary magma after possible enrichment by assimilation of crustal rocks differentiated at depth into a syenite, pyroxenite, phoscorite and carbonate fraction and that these were emplaced separately in this order. The emplacement of the carbonate fraction was of a forceful type.

The concentration of magnetite, sulphides and the rare elements in the carbonatite is the result of them becoming concentrated in residual liquors during the process of differentiation.

In the pyroxenite stage the tendency for iron to form silicates was sufficiently strong to absorb all the iron available in this fraction as ferro-magnesian silicates. With the continued withdrawal of iron accompanied by titanium the residual magma became deficient in the latter element. Much iron must have remained in the residual magma and finally separated out with the carbonatite. It is suggested that the carbonate-rich fraction was able to take up and carry along some, but not all, the copper and rare elements which portion crystallized with the carbonatite core.

The activity was terminated by the deposition of copper, uranium and thorium from a strongly charged gaseous phase which caused enrichment of these elements in already consolidated carbonatite.

VII. - COMPARISONS WITH ALKALINE COMPLEXES, ASSOCIATED WITH CARBONATITES, IN OTHER PARTS OF AFRICA

It is generally accepted that in a regional way the same structural features and associated rock types are common to alkali complexes with associated carbonatite in Africa. If they are considered in detail a number of differences are apparent. These are in the main a great variation in the range of rock types with which they are associated, accessory mineral assemblage, depth of erosion and perhaps age.

The object of the following comparisons is essentially to emphasize these differences.

The Volcanic Centres of Uganda

Four volcanic centres, Sukulu, Torora, Bukusu and Sekululo, of probable post-Karroo and pre-Tertiary age occur within 20 miles of the southwestern foot of Mount Elgon on the Uganda-Kenya border. There is a possibility of a fifth being present but its existance, owing to cover, is largely one of inference.

Davies (1947), has described the general geological features as follows:-

They are characterised by a central carbonatite core, and associated magnetite-apatite-serpentine zone. The latter is evidently the counterpart of the phoseorite at Phalaborwa. There are five concentric zones which, from the granite inwards, are as follows:-

a. granites;
b. syenites, nepheline syenites and fenites;

c. mixed rocks predominantly ijolite, but including other nepheline varieties, pyroxenites and dunites;

d. a magnetite-apatite-serpentine (phlogopite) band and

e. carbonatites.

The group has suffered considerable erosion and are considered to represent only the stumps of volcanic centres.

The carbonatites are fairly pure limestones with widespread magnetite, apatite, phlogopite, serpentine and barytes with subordinate pyroxene, pyrite, haematite and flourspar.

The contacts between the carbonatites and the magnetite-apatite-phlogopite zones are covered, but dykes of carbonate intrude the other members.

In common with the majority of alkaline complexes, in which carbonatites are developed, radioactivity is found associated with the central cores. The radioactive phases at Sukulu are described by Campbell (1952).

The core of this complex is of a composite nature and is considered to be made up of a series of intersecting cone sheets taken to indicate successive phases of eruptive activity. The carbonatite varies from fairly pure limestone, in which radioactive pyrochlore occurs, to highly ferruginous limestone showing the highest activity. The latter are the source rocks of the radioactive soil deposits of Sukulu.

The following have been recognised in the radioactive soil:-

quartz, rutile, barytes, zircon, pyrochlore, garnet, epidote, ilmenite, diopsidic-pyroxene, tourmaline, and monazite. In addition to the above, Sinclair (1955) mentions magnetite, apatite, baddeleyite, anatase and traces of copper and gold.

In the pyrochlore of the relatively pure limestone the activity is confined to grains of radioactive minerals with thorium and uranium affinities. The former predominate. The radioactive material in the ferruginous carbonatite is out of equilibrium and the activity is not due to discrete particles, but to an excess of daughter elements other than uranium and thorium.

Bowie (Campbell, 1952) considers that the ferruginous and brecciated carbonatite may have originated as normal Ca-or Mg-rich carbonatite. Later hydrothermal solutions, perhaps associated with the brecciation, may have introduced certain radioactive elements, as well as iron and barium, which have been absorbed in the ferruginous groundmass. It thus appears as if the radioactivity of the iron-rich carbonatite corresponds to the uranothorianite phase at Phalaborwa where the main concentration is associated with the maximum brecciation. The uranothorianite is, however, highly resistant to alteration and has not suffered a breakdown with subsequent leaching to give the daughter elements of the principle components. At Phalaborwa thorium also predominates over uranium.

No products of vulcanicity, except perhaps the brecciation of the phoscorite and thin cone-sheets of phoscorite in the pyroxenite rocks and glimmerite on the western flanks of Loole Kop can be found (Russell, 1954). Although differences in detail exist, the zonal structures of the Uganda occurrences and the main mineral assemblages in the carbonatites are, however, similar to those at

Phalaborwa.

The "Ring" Deposits of the Chilwa Series

Dixey (1955) has described a series of volcanic vents intrusive into rocks of either the Basement Complex or Karroo sediments and has suggested that the igneous activity took place after the Stormberg volcanic episode at the end of Karroo times.

The vents are developed over an area of 9000 square miles south and west of Lake Chilwa in Southern Nyasaland, and across the border in Portuguese East Africa. The group has been referred to as the Chilwa Series.

The Basement Complex rocks are mainly quartzo-felspathic granulites and gneisses, intruded by later alkali-granites and quartz-syenites of pre-Chilwa Series age. The rocks of the Chilwa Series include carbonatite, nepheline syenite and associated dyke-rocks cutting the earlier granite-syenite intrusives (Garson, 1954).

Sixteen vents are described. The larger are vertical pipe-like intrusions of circular or oval cross-section. The smaller ones are of irregular shape and sometimes assume a dyke-like form. In at least five of the larger and two of the smaller vents, crystalline calcium carbonate with varying amounts of iron and manganese carbonates are developed. The limestone occurs in intimate association with intrusive felspathic rocks containing between 70 and 80 per cent orthoclase. The latter normally form the peripheral portion in contact with the country rocks. Emplacement was evidently of a violent type and the surrounding country rocks are all altered to some extent.

Some of the vents are invaded by nepheline syenite others by ijolite intrusions or phonolite dykes. In general the dykes intersect the nepheline syenites and the latter the felspathic and carbonatitic rocks. At Salambidwe, syenite, vent rocks and nepheline syenite appeared in succession.

The cores of the three largest vents, Muambe, Chilwa Island and Tundulu consist of greyish crystalline carbonatite with numerous inclusions of the felspathic intrusive, iron, manganese carbonate and oxides. Pyrochlore is ubiquitous and rare-earths of the cerium-lanthanum group are characteristic of certain vents. Synchysite is frequent in the Tundulu carbonatite and monazite at Kangankunde. Fluorspar occurs occasionally.

Radioactive soil deposits at Chilwa Island and Tundulu have been described by Ostle and Taylor (1954). At both localities the main concentration of radioactive minerals occur in terra rossa type deposits overlying the vent rocks and derived directly from them.

The principle minerals in the carbonatites are carbonates, felspar and iron oxides with subordinate pyrochlore, apatite, barytes, pyrite, magnetite, fluorite, amphibole, rutile, anatase, zircon, mica, synchisite, monazite and rare cerium-bearing minerals.

The radioactivity of the soil deposits is attributed to thorium and uranium in pyrochlore, and thorium and its daughter elements which have been absorbed by goethite after the uranium has been leached away in the same way as in the Uganda occurrences. Thorium predominates over uranium.

The Carbonatites of Tanganyika

Several carbonatites are now known from this area. The Mbeya carbonatite, situated close to the 'Rukwa Trough' at latitude 8° 59' south and longitude 33° 14' east, has been described by Fawley and James (1955).

The rocks are intrusive into pre-Cambrian gneisses and consist of a central core and outer ring, both of carbonatite. The core and outer ring are usually in contact but are sometimes separated by gneiss. Both are characterised by flow lines which in the core are near-vertical and in the outer ring dip, at 85 degrees, towards the core. The gneisses are metasomatized and brecciated by the carbonatite emplacement.

The carbonatite is composed essentially of calcium carbonate with lesser amounts of magnesian carbonate. The accessory mineral assemblage is as follows:-

Magnetite, apatite, amphibole, phlogopite and vermiculite, pyrochlore, fluorite, zircon, pyrite, pyrrhotite, and minor amounts of columbite, sphene, cassiterite, ilmenite, galena, barytes, olivine and chlorite.

The Mbeya carbonatite is dated as of probable Jurassic or early Cretaceous age.

Another is known at Ngualla, Chunya District, but except for the statement that pyrochlore and columbite are present in the rock and that it is comparable in size to the Chilwa Island and Sukulu Complexes (James, 1954) the literature contains no detailed description of the occurrence.

Another pyrochlore-bearing carbonatite occurs at

Oldonyo, Dili, in the Northern Province (James, 1954).

The Carbonatites of the Rhodesias

Three alkali ring complexes, with associated carbonatites, occur in the Buhera district, Southern Rhodesia. They are, Shawa and Dorawa, situated west of Umtali in the Shawa and Dorawa Hills; and Chishanya Hill, 12 miles north of Birchenough bridge. (S. Rhod. Geol. Surv. 1952).

Those at Shawa and Dorawa are described by Mennell (1946). They perforate Archaean granite and are poorly exposed. They are tentatively dated as of probable early Jurassic age.

At Shawa the central core is a fine-grained carbonatite, highly shattered, and containing magnetite and apatite. It has a distinct banding along a NW-SE strike. A zone of serpentine with veins of magnetite lies next to the core. This is followed by dunite and ijolite and an outer ring of syenite, veined by pyroxenite similar to that in the syenite itself (Macgregor, 1947). A zone of shonkinite lies between the dunite-ijolite group and the syenite.

At Dorawa the core consists of fine-grained magnesian carbonate with magnetite, and asbestiform iron amphibole and mica. Outcrops of magnetite-rich rock, containing up to 69 per cent metallic iron, apatite and vermiculite mica occur mainly around the carbonatite. These rocks grade into apatite rocks with only accessory magnetite and subordinate nepheline, pyroxene, mica and felspar. Pyroxenite penetrates the apatite rock in places. The outer ring of the complex is formed of syenite.

The carbonatite at Chishanya Hill is described

(S. Rhod. Geol. Surv. 1952) as an irregularly shaped mass, parts of which are highly contaminated with magnetite and apatite. The literature does not contain any description of the geological setting of this carbonatite nor any reference to the detailed mineralogy or possible radioactivity of any of the three. That the first two are of the Uganda type is obvious from the descriptions.

In Northern Rhodesia there is a composite carbonatite plug in which iron, manganese, pyrochlore and phosphate minerals are present. It is associated with syenite (Bassett, 1954). Besides the reference to it as the Nkumbwa Hill feature (Sinclair, 1956) the locality is uncertain.

The South African Occurrences

Several examples where limestone occurs in association with igneous rocks and intrusive veins of carbonate are known from South Africa. Only three major occurrences of definite carbonatitic type are, however, known. These are, Palabora, Spitzkop and Glenover.

The Alkali Complex at Spitzkop has been well described. (Shand 1921; Strauss and Truter, 1950). In the more recent paper the emphasis is laid, to a great extent, on the results of fenitisation of the country rocks.

The complex is situated in the Northern Transvaal, near the Pokwani Plateau, three miles east of Malaita at latitude 24° 58' south and longitude 29° 50' east.

It is intruded into Bushveld granite and granophyre, fenitisation of which has given rise to irregular outer zones of alkali granite, quartz syenite and umptekite. These are followed by fayalite diorite, theralite, melteigite, jacupirangite, pyroxenite, ijolite and carbonatite. Ring dykes of foyaite are intrusive into the ijolites and theralites. Radial dykes of foyaite, tinguate and dolerite occur in the complex and surrounding country rocks.

The rocks of undoubted intrusive nature belonging to the complex are, pyroxenite, red ijolite, dykes of foyaite and tinguaite, and carbonatite. It is tentatively suggested (Strauss, 1950) that a peridotitic magma gave rise to the complex and that the alkali rocks and carbonatite were developed by differentiation. The sequence of events sketched by Strauss and Truter are as follows:-

The eruptive cycle commenced with a stock of pyroxenite two to three miles in diameter. Then followed the intrusion of ijolites, emanations from which fenetised pyroxenite and granite. Pyroxenite was converted to jacupirangite, fine-grained ijolite and other biotite-rich rocks. Successive surges into the granite gave umptekite, fayalite diorite and possibly theralite which were in part converted to ijolite, melteigite and jacupirangite rich in magnetite, biotite and sphene during a third surge of emanations. After metasomatism and waning pressure ring dykes of foyaite followed by carbonatite closed the intrusive cycle.

The carbonatite is described as a composite body in which the following types occur:-

1. A narrow, complete, outer zone of medium- to coarse-grained, gray calcitic-limestone (alvikite) with apatite and magnetite and having a distinctly banded structure.
2. Fine-grained dolomitic-limestone (beforsite) with abundant apatite and magnetite and accessory pyrite forms

the central portion. This body has a thin laminated structure.

Veinlets and dykes of carbonate cut the alvikite and beforsite and the latter is also cut by ijolite, foyaites and fayalite diorite. The dykes of carbonatite contain pyrite, amphibole and serpentinous material. Xenoliths of alkali rocks occur in the carbonatite.

Strauss has suggested that the outer ring of alvikite forms a ring dyke and the central beforsite an undecapitated ring dyke which was emplaced slightly later under conditions of waning magmatic pressure in accordance with Anderson's (1936) and von Eckermann's (1948) ideas.

The age of the complex is a matter of conjecture but it is most likely of post-Waterberg and pre-Karroo age (Strauss, 1950).

In general the radioactivity of the complex is well below that of the adjoining Bushveld granite and granophyre. While the main carbonatite mass is devoid of activity a circular zone up to 100 feet in width of dark-coloured streaky carbonatite, within the beforsite mass, gives significant readings in the field. Autoradiographs, of this material, show the activity to be confined to small veinlets filled with secondary material. It is present in insufficient amounts to allow identification.

A vein of carbonatite on the farm Magnet Heights to the north-east (Strauss, 1950) is regarded as satellitic to the Spitzkop Complex. The carbonatite consists essentially of carbonate minerals with much chert and accessory pyrrhotite, sphalerite and some pyrite. No radioactivity is known to be associated with the vein.

<u>The Glenover Complex</u> was discovered by Dr. H.N. Visser of the South African Geological Survey. It is situated on the farms Glenover 43, Houndslouw 38, and St. Agnesfontein 59 in the Waterberg district, at latitude 23° 53' south and longitude 27° 10' east. The complex is described by Verwoerdt (1956) in an unpublished, Atomic Energy Board, interim report.

It is intrusive into sediments of the Loskop System which are altered to felspathic rocks. The complex consists essentially of perknite and carbonatite. The latter has a central core of agglomerate.

The perknite is exposed along the northern boundary between the felspathic rocks and the carbonatite. It consists of diopside, biotite altered to vermiculite and magnetite with accessory apatite, felspar and calcite. The carbonatite is a dolomitic-calcitic limestone with accessory magnetite, apatite, diopside, phlogopite and fluorite. It contains minor amounts of chondrodite, hornblende, rutile, sphene, columbite and specks of sphalerite, chalcopyrite and arsenopyrite. The exact relationship of the carbonatite to perknite is not known. The agglomerate forms a circular mass, 400 yards across in the centre of the carbonatite. It consists essentially of fragments of Loskop sediments with introduced apatite and magnetite. Verwoerdt has suggested that the agglomerate is a xenolith caught up in the carbonatite.

The carbonatite and agglomerate are radioactive. In general the activity increases from the contact inwards reaching its peak on the agglomerate. The activity is due to columbite and its alteration products.

The South West African Occurrences

In South West Africa a broad belt of repeated late Karroo alkali complexes stretches from Cape Cross, north-east, to a point near Okorusu. Carbonatite is associated with alkali rocks at Eisenberg and Etaneno, in the southern half of the volcanic belt, and Okorusu in the northern half.

At all three localities carbonatite and perhaps foyaite have perforated granite and marble. The carbonatites have distinct ferruginous portions in which radioactive material is present.

The occurrence on the farm Eisenberg 78, is situated at latitude 20° 50' south and longitude 16° 10' east, five miles north-west of the village of Kalkfeld. The iron ore is described by Stahl (Dixey, 1955) as occurring in crystalline limestone with nepheline syenite at the centre of a crater-form ring formed by granite and partly by crystalline limestone.

The writer visited Eisenberg during 1956 and found the occurrence to be essentially as follows:-

The outer ring, which has a pronounced geomorphological expression, consists of Archaean granite, and younger Damara granite and marble. The outer ring of country rocks is separated from the central carbonatite hill by a poorly exposed zone of foyaite occupying the intervening lowlying ground. The carbonatite contains xenoliths of granite. It is characterised by a central portion, enriched in disseminated iron and radioactive material. This portion is in gradational contact with the main carbonatite mass. Carbonate dykes cut the country rock. The carbonatite, itself, is cut by near-vertical dykes.

A sample of the ferruginous carbonatite was submitted by the Tsumeb Corporation to the Geological Survey, Pretoria. The radioactive mineral was identified as thorianite. The following elements were identified spectrographically:- Mg, Ca, Sr, Ba, Si, Na, Al, Sn, Mn, K, Pb, and the rare-earths Y, Nd and Ce. (Analyst H.D. Russell).

The brecciated nature of the outer ring suggests that the carbonatite intrusion was violent. The pronounced geomorphological expression of the outer ring is also suggestive of this. The intrusion having brecciated and folded the country rocks to give them their present form. There is abundant evidence that the Damara marble was remobilized and now appears to have intruded the actually younger Damara granite. The central iron-rich radioactive carbonatite is probably the result of metasomatism by late mineralizing emanations.

The second occurrence on the farm Etaneno 44, is at latitude 20° 45' south and longitude 16° 17' east, to the north-west of Eisenberg. Similar geological conditions prevail here. Ferruginous and fairly iron-free carbonatites associated with foyaite occur in a framework of Damara marble and granite. A zone of fenetised-granite lies between the foyaite and unaltered granite. Radial dykes of carbonate cut the country rocks. Radioactivity is associated with both types of carbonatite but here the maximum activity is found in a dirty-looking carbonatite containing only small scattered crystals of iron. The radioactive material is finely disseminated throughout the ferruginous carbonatite and not as discrete particles. The mineral responsible for the activity has not been identified.

Here again the complex has a good geomophological expression.

At Okorusu 88, in the Otjiwarongo district, at latitude 20° 2' south and longitude 16° 50' east there is a large deposit of fluorspar and iron ore. Stahl (Dixey, 1955) has described the deposit as follows:-

"At Okorusu a horse-shoe-shaped ridge or broken ring appears, consisting partly of intrusive rocks of the foyaite series and partly of altered rocks of the Basement Complex and 'tuffs'. The rocks of the horse-shoe include also beds of limestone or dolomite and quartzites. These are rich in magnetite and fluorite". Slight radioactivity is associated with the ferruginous carbonate rock.

There is no doubt that geological conditions similar to those at Eisenberg and Etaneno exist at Okorusu and that Stahl's limestone may be a carbonatite.

The age of none of the three occurrences can be firmly fixed but there is no evidence to suggest that they do not belong to the same epoch as the other alkali complexes in South West Africa of post- or late-Karroo age.

The General Features of Carbonatites

Carbonatites are intrusive, calcium- and/or magnesian-rich, carbonate rocks of volcanic origin. They are normally associated with several types of undersaturated soda- or potash-rich rocks. These complexes commonly form well-developed ring-structures, in which the carbonatite is normally circular in outcrop and forms the core or central part. The volcanic piles have mostly been weathered-down to the lower part of the original volcanic neck. Intrusive carbonate rocks also occur as cone sheets, dykes and breccia zones (Fawley, 1955).

Two main types can, broadly speaking, be distinguished. These are:-

a. Those in which carbonatite, phoscorite, mixed rocks of ijolite or pyroxenite types and nepheline syenite and/or syenite occur;
b. where the mixed rocks are absent and carbonatite is associated with nepheline syenite and/or syenite.

The Uganda, Southern Rhodesia, Phalaborwa and Spitzkop occurrences are typical of the first type. Those of the Chilwa Series, Glenover and possibly South West Africa are typical of the second. The exception is Mbeya in Tanganyika where carbonatite only is developed. It is possible that the South West African carbonatites are of the Mbeya type and the foyaite fenetised country rock. The rock types here are not observed in contact and it is impossible to say if the foyaite is an original primary igneous rock.

The carbonatites are characterised by flow structures. In the Southern Nyasaland occurrences these structures are regarded as the result of upward movement under high pressure (Garson, 1955).

The principle accessory mineral assemblage is magnetite, apatite and mica. The presence of pyrochlore and barytes is a common feature of the carbonatites of the Chilwa Series, Uganda and Tanganyika. Common constituents of most are flourite, rutile, zircon and pyrite. Pyrrhotite is sparingly developed at Mbeya and Magnet Heights. Specks of chalcopyrite occur at Glenover while copper sulphides are prominent at Phalaborwa.

Radioactivity, due to thorium and its daughter elements in minerals of the columbate and tantalate group, and concentrated in the ferruginous parts, is a common feature of most carbonatites. Where uranium is present it is always subordinate to thorium. Only at Phalaborwa is uranium of significance.

The main differences become apparent when the subordinate accessory mineral assemblages, particularly the absence or presence of sulphides, are contrasted. As the elements were introduced at a late magmatic stage it is probable that the accessory minerals present reflect the depth of erosion of the original volcanic pile. This is no new idea. Stringer (1956) in describing the Chambe Plateau Complex in Nyasaland, which consists of multiple ring intrusions of syenite, has suggested that the absence of carbonatite may be because denudation has not gone deep enough.

Dixey (1946) has pointed out that from Uganda southwards the degree of erosion of the alkali complexes increases. The average elevations at Spitzkop, Glenover and Phalaborwa are 5000, 3000 and 1200 feet, respectively. The radioactivity and the proportion of sulphides present increase as the average elevation decreases. It thus seems likely that the Palabora Complex is exposed at an erosion level lower than that at Dorowa, Shawa, Glenover and Spitzkop. If this be true deep drilling may disclose increased radioactivity and copper mineralization in depth at the latter two occurrences.

There is still a lot of disagreement as to the age or ages of the carbonatites. This is largely because only in a few cases can geological evidence be found to date them. Those in Central Africa, which are all associated with the Rift valley line of weakness and appear to be genetically connected, are most likely of late Jurassic or early Cretaceous age. The South West African ones are regarded as late or Post-Jurassic.

The South African examples all perforate rocks of Pre-Cambrian age, while at Phalaborwa the complex is intruded by dolerite dykes. These dolerite dykes are generally regarded as of early Jurassic age. Isotype analyses indicate a probable age of 1960 x 10^6 years for the Palabora carbonatite (Russell, 1954) making it of the same age as the uraninite in the Witwatersrand system i.e: pre-Cambrian (Wasserstein, 1954).

While the local carbonatites cannot be related to the Central African ones by any structural tie-up with the Rift Valley, the characteristic rock types, mineral assemblages, and the presence of basically the same radioactive minerals, however, suggests that they are most likely also of Jurassic age. No geological evidence to the contrary can be found.

VIII. - ECONOMIC GEOLOGY

The carbonatite is primarily a copper proposition. Since, however, the deposit is low grade, calling for mining on a large scale, the production of saleable by-products must be considered. These possible by-products are uranium, thorium, magnetite and agricultural lime. It is possible that when the magnetite is removed the carbonate might be treated for apatite removal.

Taken in conjunction with the surface distribution of radioactive material, as indicated by the isorad map (fig. 5) and accepting the sympathetic uranothorianite-copper relationship, the assay plans (figs. 22, 23 and 24) suggest that the most favourable ground is an irregularly defined zone of enrichment, the 'inner' zone, elongated in an east-west direction. This zone has a possible width of 400 feet and extends over a strike of approximately 1600 feet. Drilling has established the continuation of this zone to at least a depth of 1893 feet (Bore-hole 7) at which depth the bore-hole was stopped.

The mineralization, being coarse-grained and of an erratic nature, gives rise to a great diversity in the ore content of the carbonatite. This makes an average determination of specific gravity difficult. Determinations were made on bore-hole cores taken at approximately every 10 feet. By averaging these figures a mean specific gravity of 3.13 was found, and was used in subsequent calculations of ore reserves.

Two different mining possibilities exist depending on the scale of mining adopted and the beneficiation costs. Since, such information is not yet available, it is necessary to consider both possibilities. These are, firstly, the exploitation of only the 'inner' zone and secondly, of the whole mass of carbonatite. Three separate geological or probable ore reserve estimates have, therefore, been made. These are as follows:-

a. The 'inner' zone which represents the most promising area;
b. the 'outer' zone, where higher concentration of apatite and lower concentration of uranothorianite and copper are expected;
c. the carbonatite as a whole.

a. The 'Inner' Zone

In assessing the mean grade of this zone the estimate of geological ore reserves was based on the following information:-

Information obtained from	Length of zone sampled in feet	Mean Values		
		e-U_3O_8 lbs/ton	Cu %	P_2O_5 %
Bore-hole 2	126	0.14	0.92	2.6
Bore-hole 3	220	0.43	1.45	0.7
Bore-hole 4	256	0.37	1.72	0.8
Bore-hole 5	678	0.20	0.99	1.5
Bore-hole 6	262	0.29	0.65	4.1
South adit	259	0.34	1.20	1.3
2 Drive east	250	0.27	1.43	1.1
3 Drive west	434	0.46	1.59	0.9
4 Drive west	433	0.42	1.18	1.2
1 W x - cut north	90	0.37	1.35	0.7
T.O.C. Bh. 1	291	0.40	0.79	-
T.O.C. Bh. 2	338	0.26	0.72	-
T.O.C. Bh. 3	270	0.30	0.62	-
T.O.C. Bh. 5	330	0.35	0.85	-
Total footage sampled	4237			
Mean grade		0.33	1.11	1.45

Accepting these mean grade[1] figures and having determined, by planimeter, a total area of 582, 321 sq.ft.[2] of ore the estimated tonnages[3] per 100 feet depth are 5,700,000 tons in the 'inner' zone. This gives a tonnage of 63,300 tons copper, 1,881,000 lbs of equivalent uranium oxide and 82,700 tons of P_2O_5 per 100 feet in depth.

The mean value of 0.33 lbs/ton equivalent uranium oxide implies that the combined radioactivity of the uranium and thorium members of the uranothorianite is equal to the activity of 0.33 lbs/ton of uranium alone. It has been shown that the proportions of uranium and thorium are quite variable, but that a ratio of 1 : 2.81 should be a fair approximation if applied to a sufficiently large tonnage of ore. On this basis the 'inner' zone may contain uranium to the order of 490,000 lbs and 1,390,000 lbs thorium per 100 feet.

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1. In this and subsequent tabulations the mean grade was calculated by weighting the mean values with the length of the zone sampled in feet and dividing the total weighted values by the total length sampled.
2. Excluding dyke material.
3. Tonnage expressed as short tons.

b. The 'Outer Zone

The following results are available from inclined bore-holes and underground prospecting which intersected the 'outer' zone.

Information obtained from	Length of zone sampled in feet	Mean Values		
		e-U_3O_8 lbs/ton	Cu %	P_2O_5 %
Bore-hole 2	336	0.10	0.47	3.1
Bore-hole 3	412	0.10	0.59	3.6
Bore-hole 4	236	0.11	0.57	3.4
Bore-hole 5	119	0.14	0.43	4.9
Bore-hole 6	704	0.12	0.44	5.9
Bore-hole 8	829	0.21	0.75	6.1
South adit	687	0.04	0.44	4.6
2 Drive east	236	0.15	0.40	4.2
5 Drive east	150	0.08	0.57	3.2
T.O.C. Bh. 1	210	0.08	0.36	-
T.O.C. Bh. 2	230	0.05	0.32	-
T.O.C. Bh. 3	170	0.05	0.44	-
T.O.C. Bh. 5	370	0.12	0.76	-
Total footage sampled	4689			
Mean grade		0.12	0.51	4.7

The total area in plan, excluding dyke material, is 2,546,297 sq. ft. and the estimated tonnage per 100 feet depth is of the order 24,900,000 tons. At the grades given in the above tabulation this represents 127,000 tons copper, 2,998,000 lbs cf equivalent uranium oxide and 1,162,800 tons of P_2O_5 per 100 feet in depth.

The uranium-thorium ratio, 2.81, indicates that the 'outer' zone contains possibly 780,000 lbs uranium and 2,200,000 lbs thorium per 100 feet in depth.

c. The Approximate Grade of the Carbonatite as a Whole

In assessing the grade of the whole body it must be stressed that any such calculation is very much an approximation as much of the carbonatite has not been sampled.

It occupies an area of 3,128,615 sq. ft. and represents a tonnage of 30,600,000 per 100 feet depth. Grades applicable to this tonnage are best calculated, from the available information, by dividing the sum of the tonnages obtained for copper, equivalent uranium and P_2O_5 respectively, in the 'inner' and 'outer' zones by 30,600,000. On this basis the following grades were calculated:-

Copper 0.62 per cent, equivalent uranium oxide 0.16 lbs/ton and phosphate, expressed as P_2O_5, 4.1 per cent.

The carbonatite at best will prove to be only a low-grade copper proposition in which by-products will of necessity bear part of the cost structure. Besides uranothorianite and perhaps apatite, magnetite and agricultural lime may be economically recoverable.

The figures derived from visual assay of magnetite indicate that the overall magnetite content is of the order 27 per cent. The titanium content is low and appreciably less than one per cent. A recent chemical analysis of this magnetite (table II) suggests that the phosphorous content will also prove to be low although the magnetite is intimately intergrown with some apatite. This latter aspect cannot be adequately assessed until details of the eventual metallurgical process are known.

With an average grade of 27 per cent and at the square footages already mentioned available magnetite should be of the order 1,500,000 in the 'inner' zone, 6,700,000 in the 'outer' zone and 8,300,000 tons per 100 feet in the whole carbonatite. This magnetite should be available, as a by-product, at very little extra cost.

The carbonatite probably contains between 60 to 70 per cent magnesian limestone containing 69.2 per cent $CaCO_3$ and 22 per cent $MgCO_3$ (table II, analysis 7). As such the magnesian limestone may be regarded as an excellent agricultural limestone supplying magnesium in addition to the calcium and is superior to the normal commercial limestones which have a $CaCO_3$ content of 60 to 70 per cent. The tonnages involved are enormous and the limestone would be available to the farming areas of Tzaneen and Nelspruit which lies on rail within a radius of 100 miles. At a nominal price of 2/6 per ton F.O.R. Phalaborwa, this agricultural lime would be of considerable economic interest.

Analysis of a bulk sample from the adit showed the presence of 0.04 per cent zirconia derived from the mineral baddeleyite. When isolated this mineral is found to be fairly coarse-grained and might become of economic interest when large tonnages are mined.

d. Conclusions

The reasonably detailed drilling programme undertaken by the Atomic Energy Board and the Transvaal Ore Company has explored the carbonatite to a depth of 600 to 700 feet, with one bore-hole penetrating to 1893 feet.

The results show a higher grade kidney-shaped body of remarkably uniform grade of copper, of the order of one per cent, lying within the carbonatite. This body has a length of some 1600 feet and a maximum width of 400 feet. On the assumption that there is no decrease in grade or dimensions in depth the ore reserves are of the order of 50 to 60 million tons per 1000 feet.

If a lowering of copper grade to 0.6 per cent is still found to be above the economic limit the ore reserves can be increased to include the whole carbonatite mass having a length of 1000 yards and a width of 400 yards. In this case the ore reserves will be of the order of 300 million tons per 1000 feet depth. In practise the limit of payability will most probably be found to lie between 0.6 and one per cent with a corresponding reduction of the total available ore reserves.

Accessory products which will be available for exploitation after the extraction of copper include urano-thorianite with a grade between 0.1 and 0.3 equivalent U_3O_8; the magnesium-calcium carbonate which is an excellent agricultural limestone; the magnetite which has a low titanium content, and a certain percentage, estimated to be of the order one to five per cent P_2O_5, of apatite.

Mining operations should present no difficulties and in the metallurgical process envisaged the separation of the ore into the components listed above would present no major obstacles.

IX. - ACKNOWLEDGEMENTS

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APPENDIX

Temperature Measurements

By far the bulk of the information appertaining to the study of heat flow in South Africa has been obtained from bore-holes drilled to intersect the Witwatersrand system. Only very limited data are available from bore-holes in other areas. As far as is known no temperature measurements have been made in bore-holes intersecting carbonatite. As the drilling was under the control of the writer the opportunity was used to attempt to throw light on the controversial problem, temperature equilibrium.

Bore-hole 7 was drilled to a depth of 1873 feet, reaching this depth on the 17th August, 1955. Temperature measurements were made, at intervals of 200 feet, on the same day, using 6-inch Zeal clinical thermometers and a few more accurate Negretti and Zambra maximum thermometers. The measurements were repeated eight months later, on the 11th April, 1956.

Use was made of a multi-thermometer assembly (Mossop, 1950) to lower the thermometers. This equipment consists of a number of metal tubes open at one end. The open end is closed with a screw top sealed with a soft copper washer. Three thermometers, each in their protective tubes, were enclosed in an outer container split longitudinally in halves. This outer container was clamped to rubber sheathed wire by screwing the two halves together. The string of containers, after lowering to the required depth in the bore-hole, were left for one hour.

Thermometers, after recovery form the bore-hole, were transferred with the minimum delay to an ice-cooled water bath. Temperatures were read with the bulb and portion of the stem immersed. As the thermometers were calibrated for total immersion an emergent stem correction was applied according to the following formula (Carte[1], 1954):-

$$c = K\,n\,(T - t)$$

where n = length of emergent column in degrees.

T = thermometer reading.

t = stem temperature.

K = differential expansion coefficient for the thermometric liquid and the particular glass.

For mercury-filled, centigrade scale, thermometers (Negretti and Zambra) K = 0.00016.

For mercury-filled, fahrenheit scale, thermometers (Zeal) K = 0.00009.

The results tabulated in table X represent the mean of three thermometer readings, after applying the emergent stem correction, at each particular depth. Obviously anomalous results were discarded and the measurements repeated until fair agreement between three readings at each depth was obtained. The results are presented graphically in figure 25. Although the carbonatite is extremely heterogeneous the temperatures lie reasonably closely on a straight line and the depth-temperature curves are represented by the best-fit straight line drawn through the observed temperatures.

The data obtained supports Bullard's conclusion (1947) that temperatures are upset by drilling and that a considerable time must elapse before equilibrium is restored. Furthermore, as the time required is related to the speed of drilling, equilibrium will come about more rapidly at the bottom of the bore-hole

Comparing the results obtained on the 11th April, 1955 with those of the 17th August, 1956 shows that an increase of 0.41° C/ was found at 400 feet depth. The curves intersecting at 1500 feet, while at 1800 feet the temperature had decreased by 0.24° C. A mean geothermic step of 150 ft/1° C, obtained the day drilling stopped, increased to 160 ft/1° C eight months later.

The mean geothermic step for carbonatite lies between the means obtained for the Karroo system and the Ventersdorp lava, 130 and 230 ft/1° C, respectively (Bouwer, 1952). Conductivity determinations have not been done on samples of carbonatite. It is reasonable to assume, however, that the mean conductivity value should lie between that of the Karroo system and the Ventersdorp lava. The sandstones, dolerites and shales of the Karroo system have conductivities of 0.0047, 0.0050 and 0.0057, respectively (Carte[2], 1954) and the Ventersdorp lava 0.0075 (Carte, 1955).

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TABLE X TEMPERATURE MEASUREMENTS

BORE-HOLE No. 7

Drilling started 7-11-54
Drilling stopped 17- 8-55

Depth	Temperature °C		Difference	Temp. Gradient		Geothermic Step	
	17-8-55	11-4-56		17-8-55	11-4-56	17-8-55	11-4-56
200	24.64	-	-	-	-	-	-
400	25.94	26.35	+0.41	1.30	-	154	-
600	27.39	27.79	+0.40	1.45	1.44	138	139
800	28.75	28.90	+0.15	1.36	1.11	147	180
1000	30.08	30.01	-0.07	1.33	1.11	150	180
1200	31.45	31.40	-0.05	1.37	1.39	146	144
1400	32.54	32.70	+0.16	1.09	1.30	184	154
1600	33.98	33.80	-0.18	1.44	1.10	139	192
1800	35.44	35.20	-0.24	1.46	1.40	137	143
			Mean values	1.35	1.26	150	160

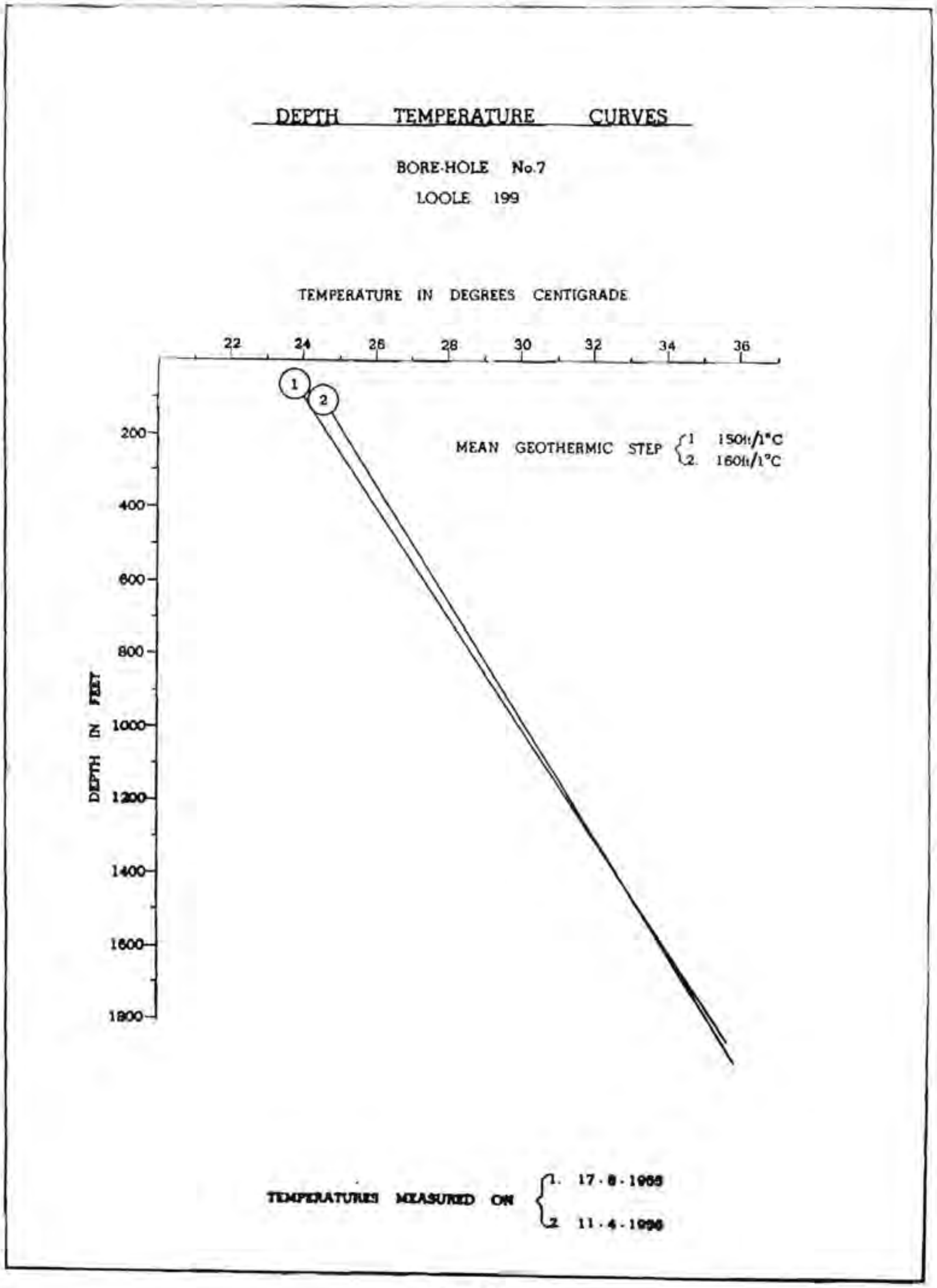
DEPTH TEMPERATURE CURVES
BORE-HOLE No.7
LOOLE 199
TEMPERATURE IN DEGREES CENTIGRADE
22
24
26
28
30
32
34
36
1
2
MEAN GEOTHERMIC STEP 1. 150ft/1°C 2. 160ft/1°C
200
400
600
800
1000
1200
1400
1600
1800
DEPTH IN FEET
TEMPERATURES MEASURED ON
1.
2

Fig 26.

GENERAL NOTES ON PLATES
XVII - XXIII

The macrophotographs were obtained from polished specimens of carbonate core, specially selected for radioactivity content, to show the distribution of uranothorianite in respect to the various other minerals present.

The autoradiographs were obtained by exposing the selected specimens to x-ray film for a period of 120 hours.

A sketch, positioned between the macrophotograph and autoradiograph, of each specimen has been provided to relate macrophotographs and autoradiographs. The predominant mineral is outlined and shaded. Other points of interest are lettered. The points at which uranothorianite occurs are shown by black spots.

Plate XVII

The distribution of uranothorianite in relation to phlogopite and calcite.

a. phlogopite (shaded);
b. calcite.

Uranothorianite shows no preference for either mineral and is distributed at random throughout the specimen.

Natural size.

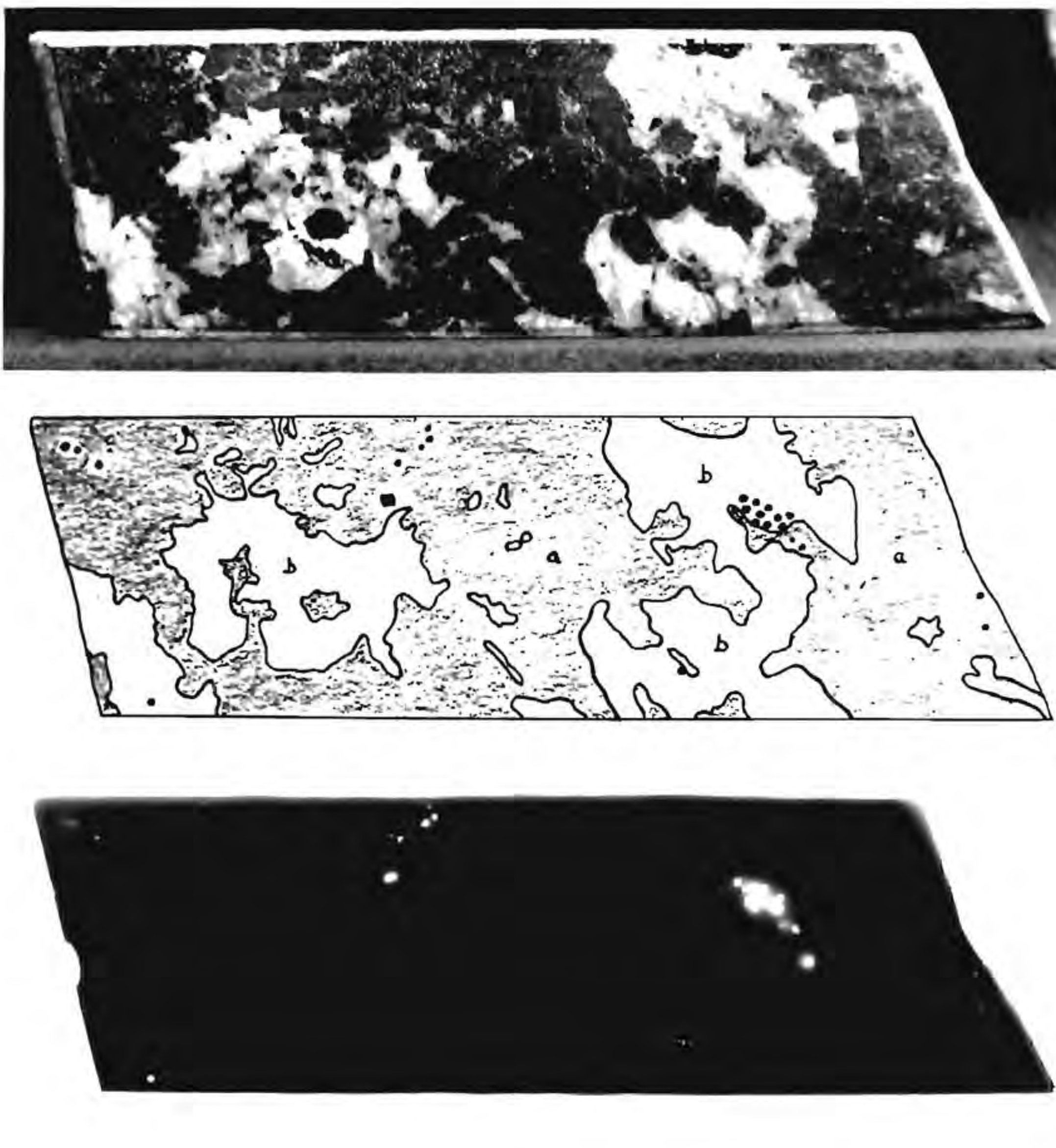

Plate XVII

Plate XVIII

The distribution of uranothorianite in relation to chalcocite, magnetite and calcite.

a. chalcocite (shaded);
b. magnetite in part replaced by valleriite;
c. valleriite at the margins of massive magnetite;
d. a coarse-grained aggregate of magnetite, chalcocite and apatite in calcite;
e. is the same as (d) with chondrodite and only subordinate apatite.

Uranothorianite is here confined exclusively to calcite (white).

Natural size.

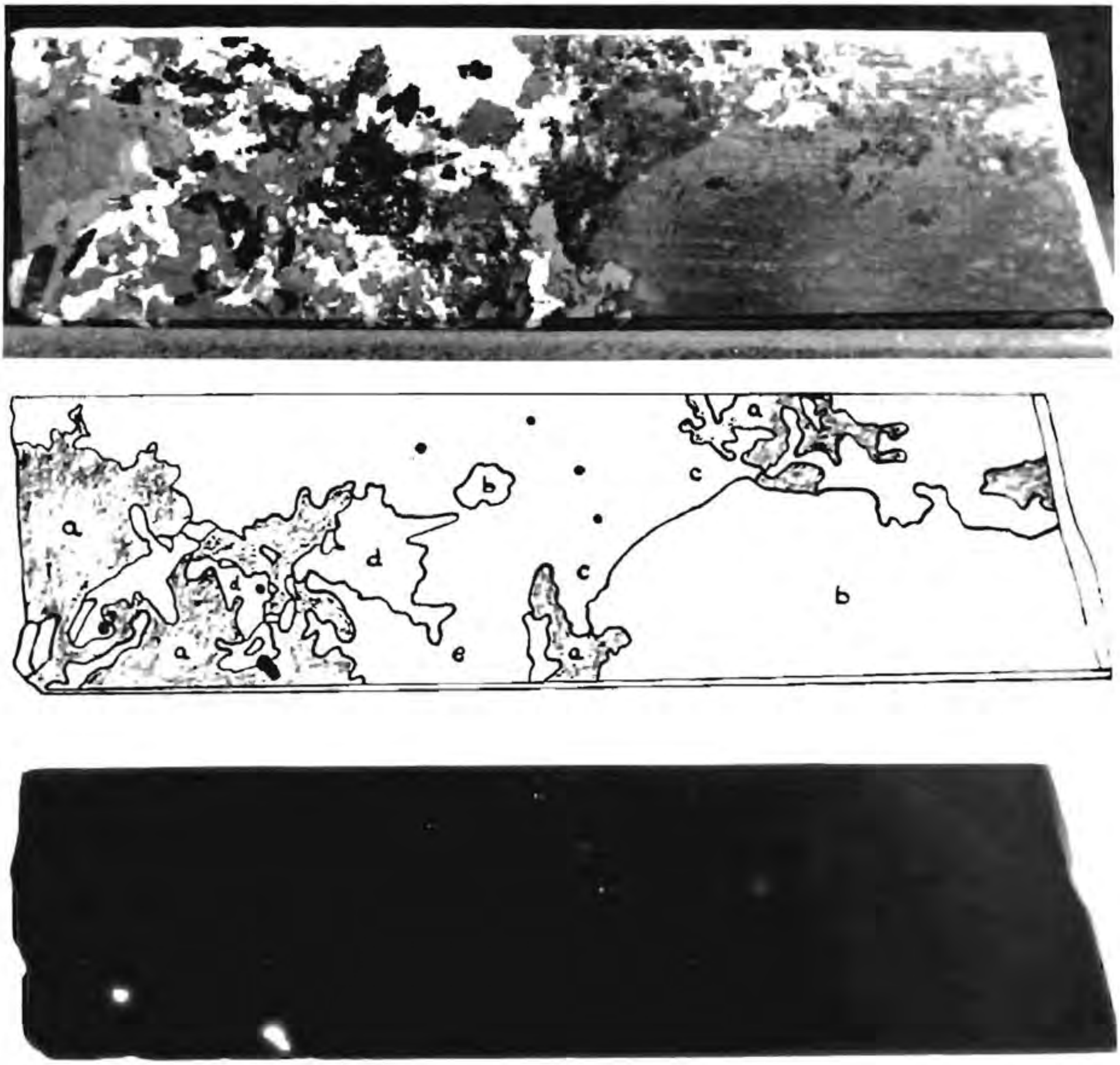

Plate XVIII

Plate XIX

The distribution of uranothorianite in relation to magnetite and calcite.

a. magnetite (shaded) with inclusions of calcite (white) and replaced by ramifying veinlets of valleriite;
b. calcite replaced by serpentine.

Uranothorianite is seen to occur predominantly in the magnetite, while only isolated crystals occur in the calcite.

Natural size.

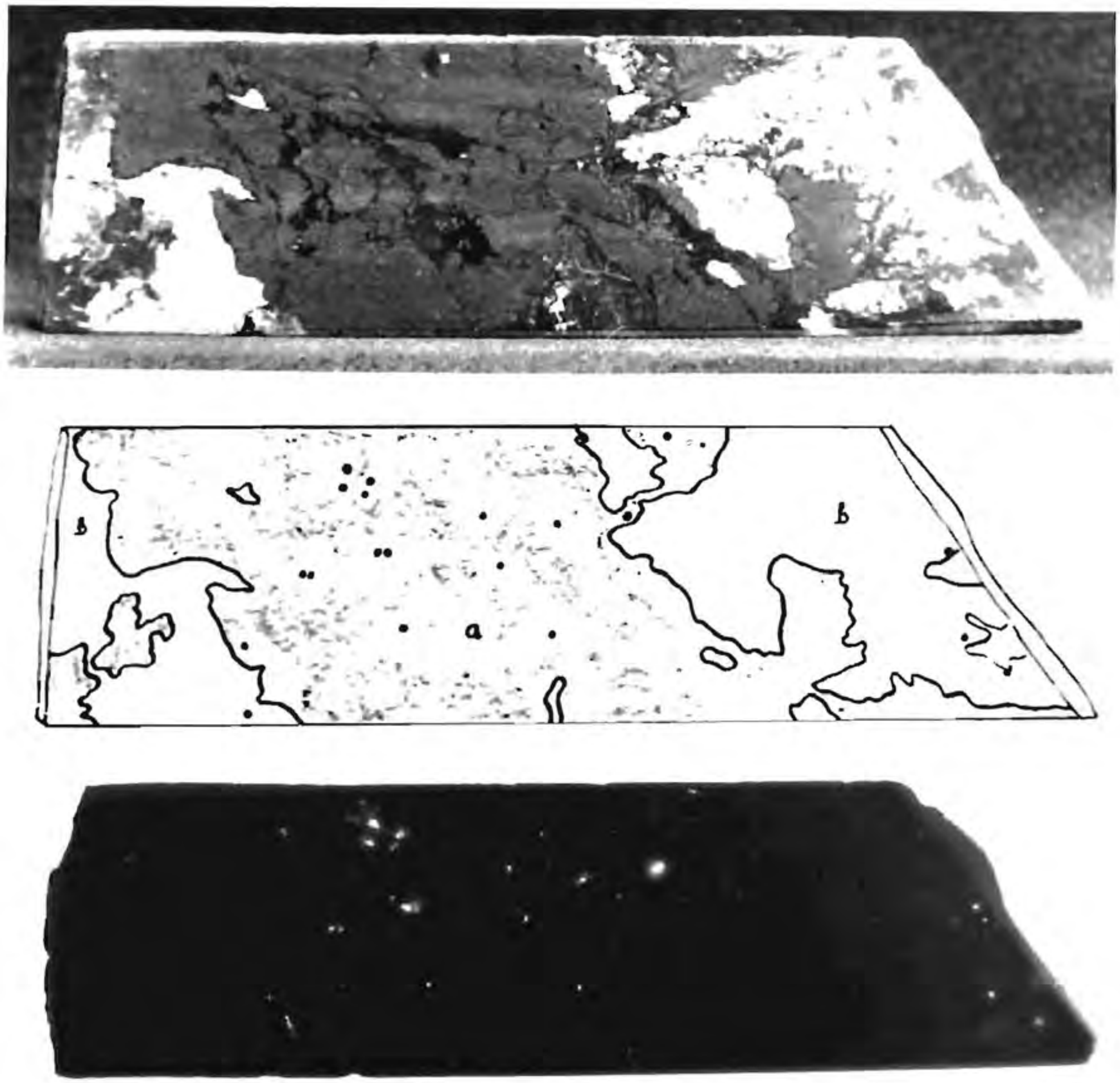

Plate XIX

Plate XX

The distribution of uranothorianite in relation to chalcopyrite, phlogopite, magnetite and calcite.

a. chalcopyrite (shaded);
b. magnetite;
c. phlogopite which chalcopyrite is replacing;
d. an aggregate of phlogopite, chalcopyrite and apatite;
e. apatite in calcite (white).

Uranothorianite is here confined exclusively to the calcite.

Natural size.

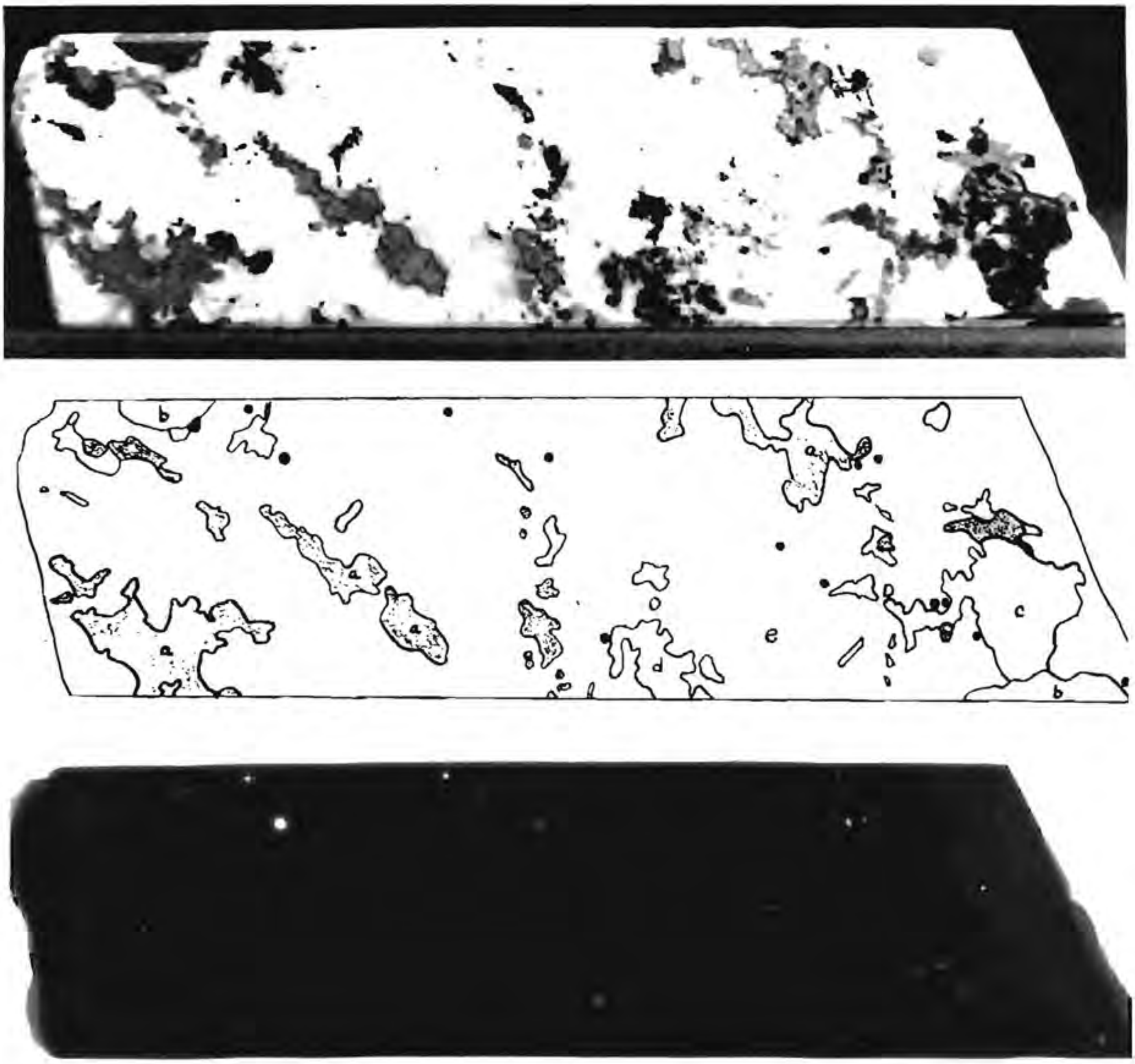

Plate XX.

Plate XXI

The distribution of uranothorianite in relation to serpentine, chalcopyrite, apatite and calcite.

a. serpentine (shaded);
b. chalcopyrite;
c. apatite;
d. calcite.

Uranothorianite is distributed at random throughout the gangue minerals and does not occur in association with chalcopyrite.

Note the large crystal of uranothorianite visible in the macrophotograph.

Natural size.

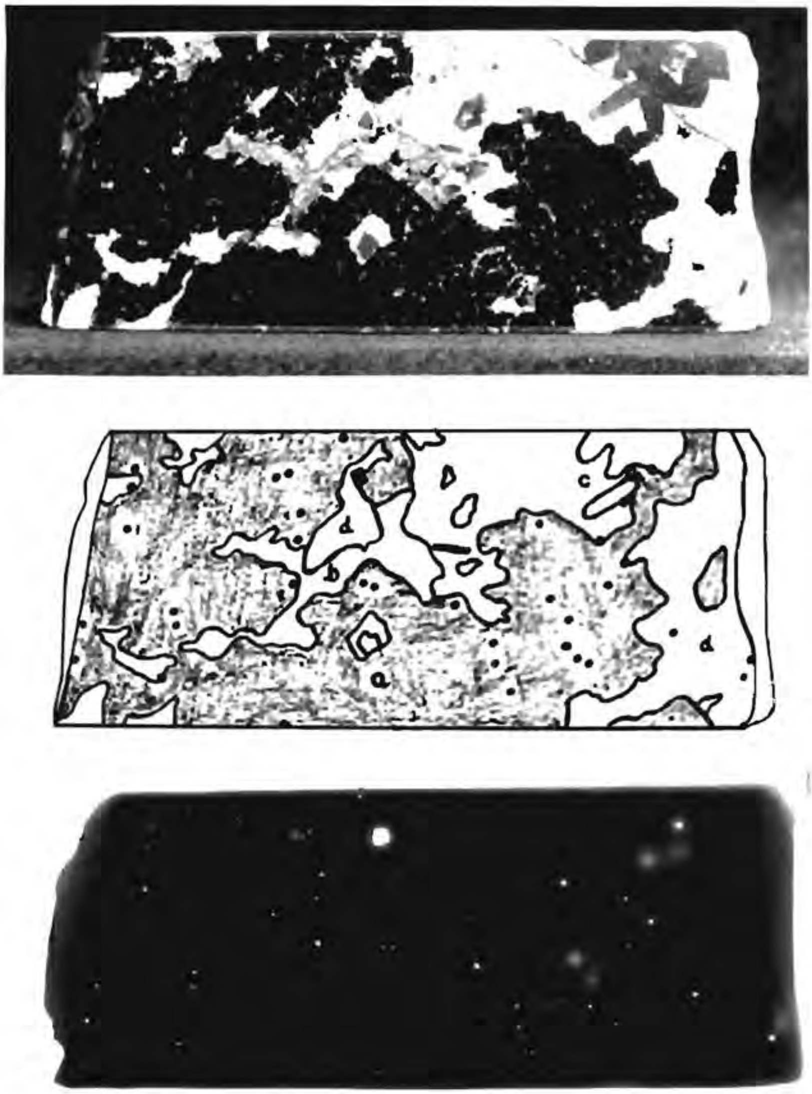

Plate XXI

Plate XXII

The distribution of uranothorianite in relation to serpentine, magnetite and calcite.

a. massive serpentine (shaded) replacing calcite by a system of veins;
b. magnetite;
c. brecciated calcite with magnetite and veins of valleriite;
d. veins of valleriite spreading from a minor localised fracture into calcite.

Uranothorianite is confined entirely to calcite and is heavily concentrated in the brecciated portion on the right.

Natural size.

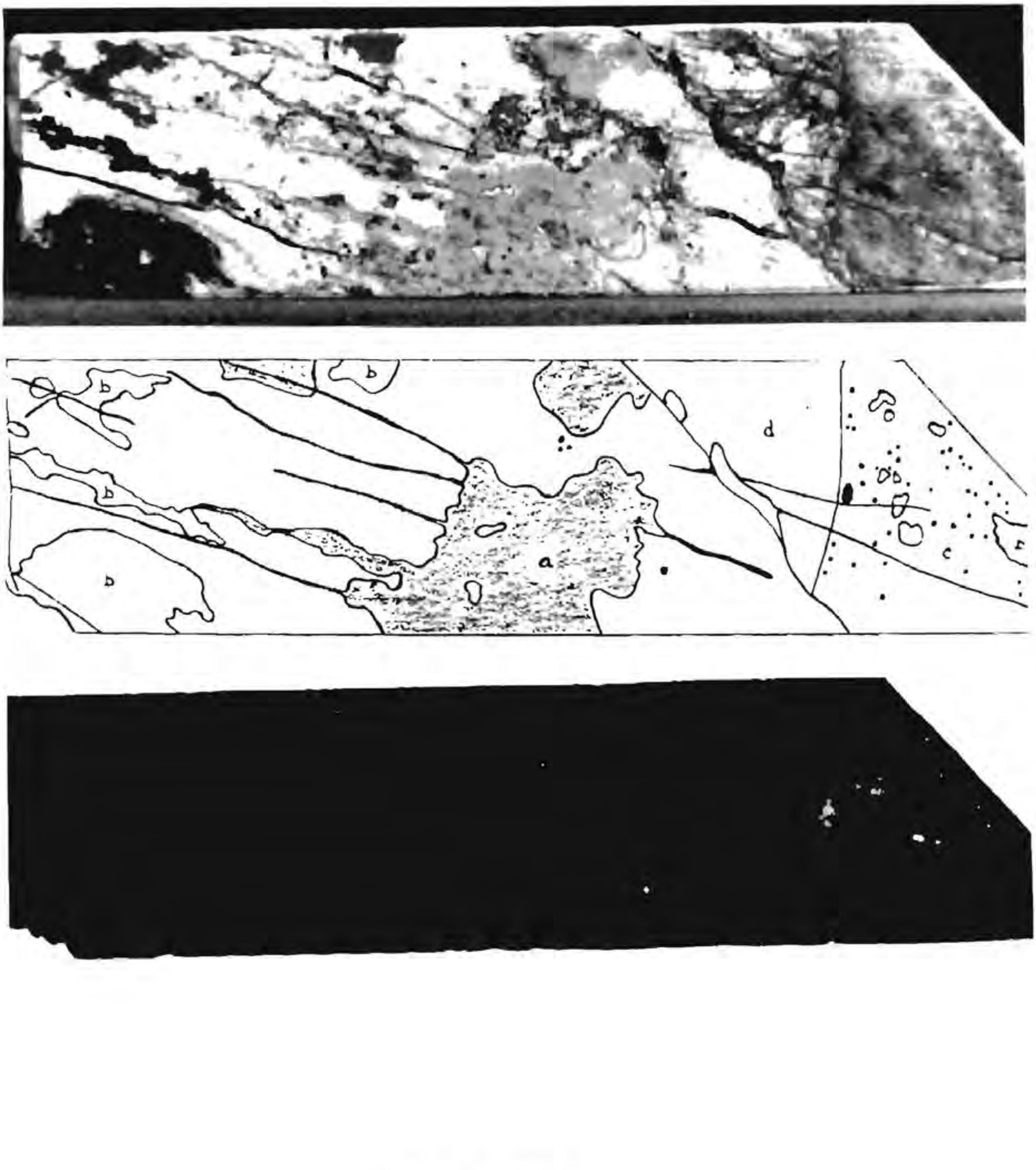

Plate XXII

Plate XXIII

Fig. A. shows the distribution of uranothorianite in relation to chalcopyrite, magnetite, chondrodite and calcite.

a. chalcopyrite (shaded) replacing magnetite at margins;
b. magnetite with inclusions of calcite;
c. calcite;
d. a crystalline aggregate of chondrodite with subordinate apatite in calcite and associated chalcopyrite.

Uranothorianite is distributed at random throughout the ganque minerals but does not occur in association with chalcopyrite.

Natural size.

Fig. B. shows the distribution of uranothorianite in brecciated carbonate. Associated are magnetite, valleriite, serpentine and calcite.

a. magnetite (shaded) partly replaced by valleriite;
b. serpentine, valleriite and subordinate chalcopyrite healing brecciated calcite;
c. chalcopyrite filling a minor joint.

Uranothorianite occurs almost exclusively in brecciated calcite.

Natural size.

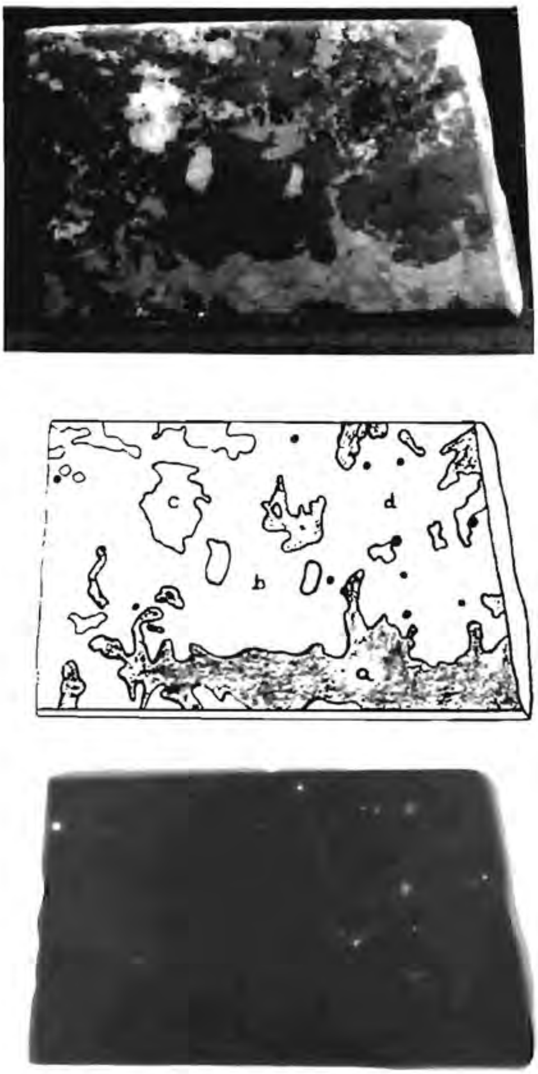

Fig. A.

Fig. B.

Plate XXIII

Plate XXIV

Fig. A. Typical hypidiomorphic granular texture shown by the non-opaque minerals. Black is magnetite replacing chondrodite (c); apatite (grey); and calcite (ca). Apparent veins are cracks in the section.

Thin section.
Nicols X 18.

Fig. B. Fine-grained aggregate of chondrodite enclosing an earlier formed apatite (dark grey) crystal.

Thin section.
Nicols X 24.

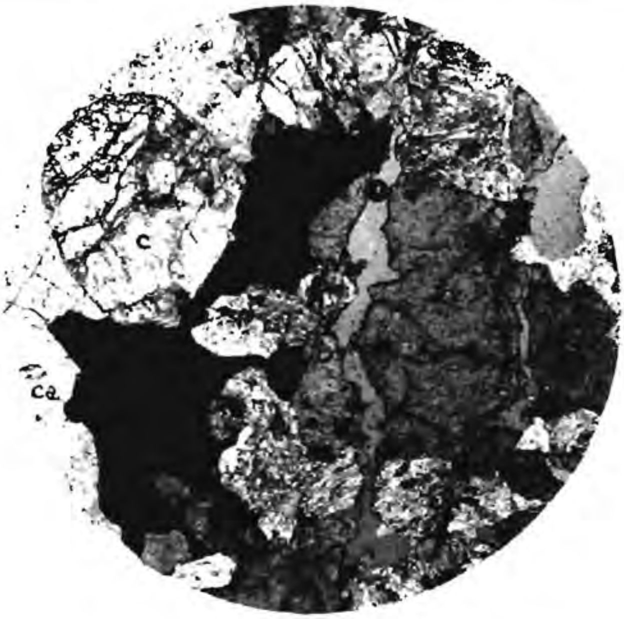

Fig. A.

Fig. B.

Plate XXIV

Plate XXV

Fig. A. Characteristic polysynthetic twinning in chondrodite (c). The chondrodite shows incipient alteration to serpentine and magnetite. Phlogopite is present between magnetite (black) and chondrodite.
(Note top edge of upper chondrodite crystal).

Thin section.
Nicols X 22.

Fig. B. Fine-grained aggregate of chondrodite crystals showing polysynthetic twinning.

Thin section.
Nicols X 30.

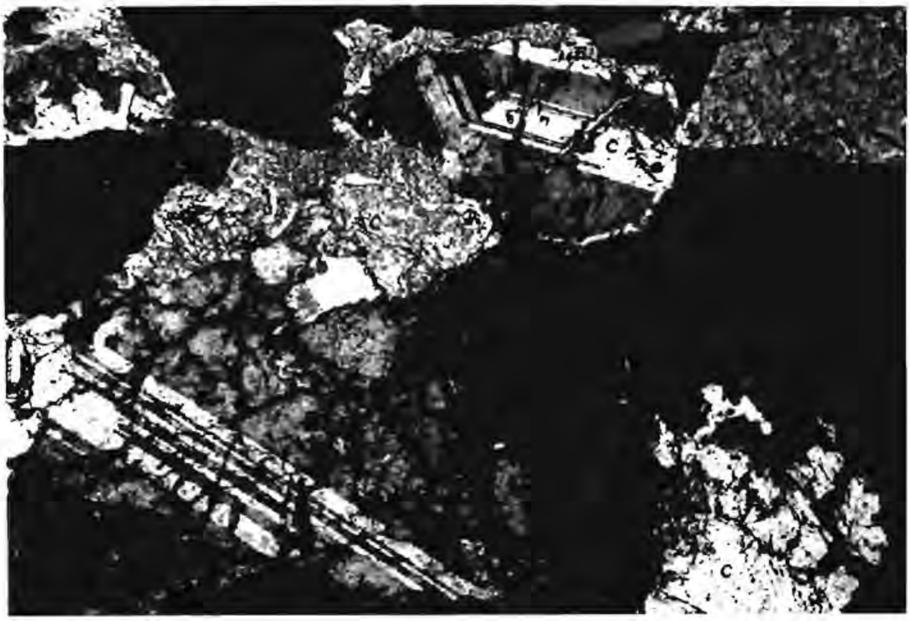

Fig. A.

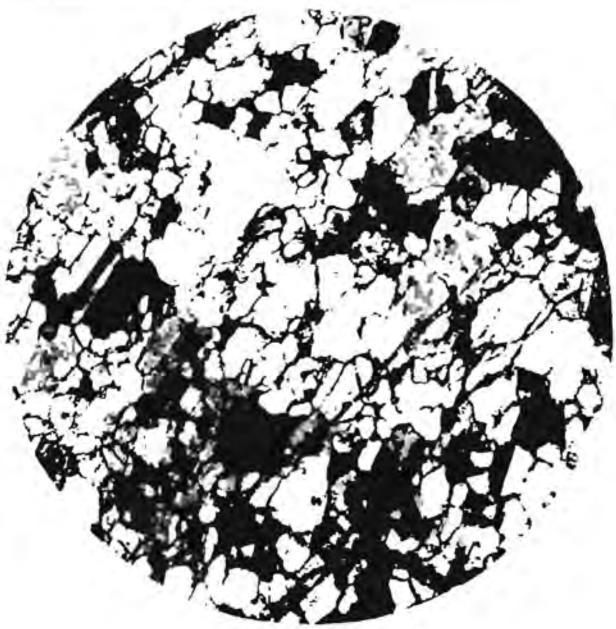

Fig. B.

Plate XXV.

Plate XXVI

Fig. A. Polygonal crystals of olivine in calcite matrix.

Thin section.
Nicols X 22.

Fig. B. Selective core-alteration of chondrodite (c) to serpentine (se). Note incipient alteration of portions of the chondrodite rim to secondary magnetite along irregular fractures. Apatite (a) is visible at the bottom. Black is magnetite.

Thin section.
Ordinary light X 34.

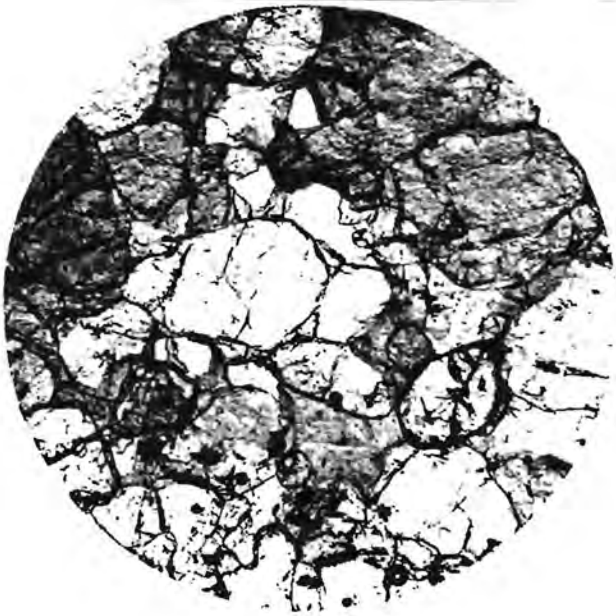

Fig. A.

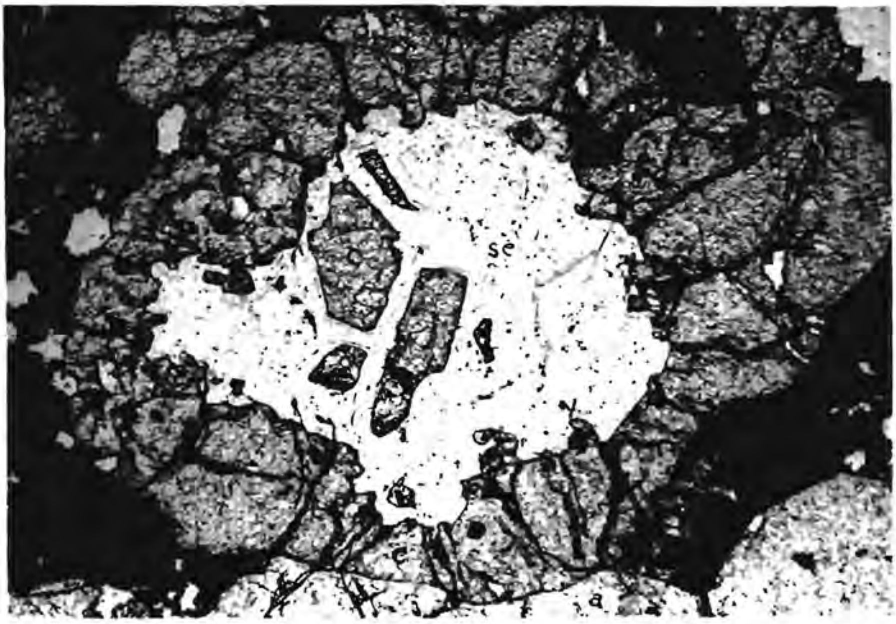

Fig. B.

Plate XXVI

Plate XXVII

Fig. A. Fribrolamellar structure of serpentine derived from chondrodite.

Thin section.
Nicols X 31.

Fig. B. Interpenetrating polysynthetic twins of baddeleyite (black) replacing chondrodite (c) and calcite (ca).

Thin section.
Nicols X 36.

Fig. A.

Fig. B.

Plate XXVII

Plate XXVIII

Fig. A. Inclusions of phlogopite (white) in magnetite (black). The phlogopite is replaced in part by magnetite along cleavage traces.

Thin section.
Ordinary light X 18.

Fig. B. Euhedral crystals of spinel (pleonaste) with characteristic octahedral form, occurring as inclusions in magnetite (black). Some of the spinel crystals are moulded on calcite (ca).

Thin section.
Ordinary light X 35.

Fig. A.

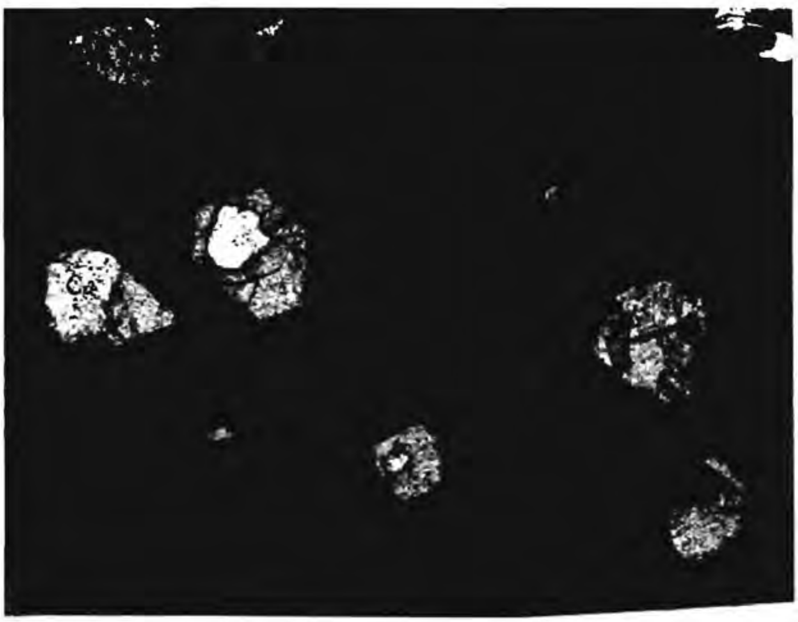

Fig. B.

Plate XXVIII

Plate XXIX

Fig. A. Valleriite (black) replacing magnetite (ma) and chalcopyrite (chp). The valleriite contains specks of chalcopyrite.

Polished section.
Ordinary light X 90.

Fig. B. Contemporaneous crystallization of magnetite (ma) and valleriite (va) replacing chondrodite by a series of veins. Chalcopyrite is present at top right.

Polished section.
Ordinary light X 28.

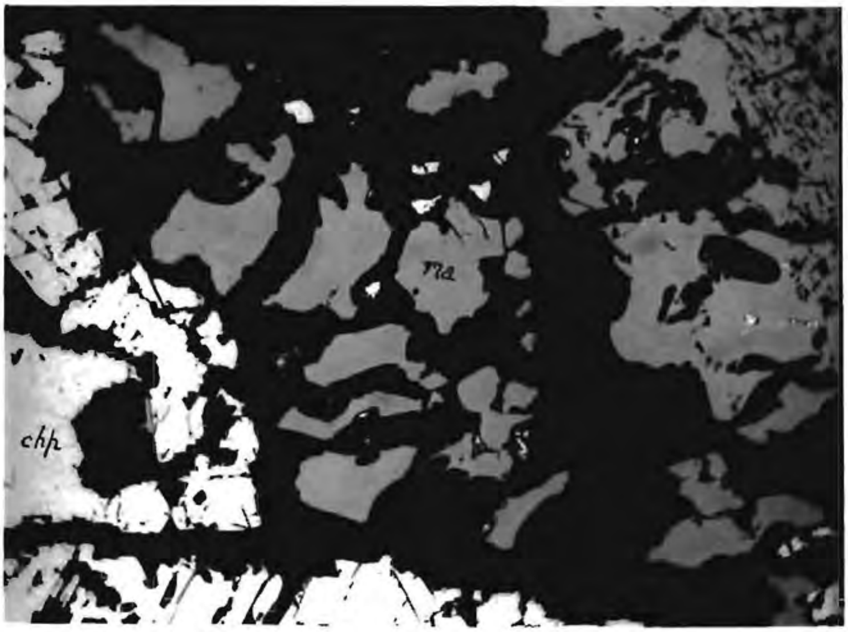

Fig. A.

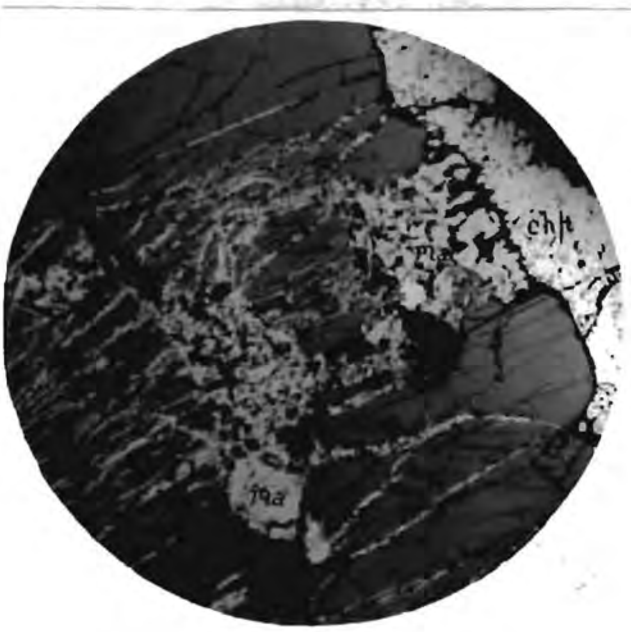

Fig. B.

<u>Plate XXIX</u>

Plate XXX

Fig. A. Contemporaneous crystallization of magnetite (ma) and valleriite (va) replacing chondrodite. Enlargement of centre of plate XXIX fig. B.

Polished section.
Ordinary light X 72.

Fig. B. Euhedral crystals of uranothorianite distributed throughout apatite (a) and calcite (ca) gangue. Magnetite (ma) contains inclusions of tabular crystals of apatite.

Polished section.
Ordinary light X 16.

Fig. A.

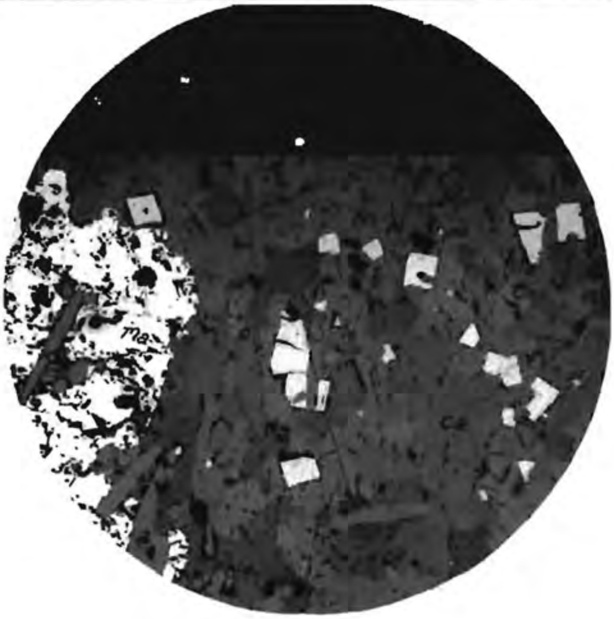

Fig. B.

Plate XXX

Plate XXXI

Fig. A. Euhedral crystals of uranothorianite in gangue. The crystals are moulded on apatite (a) and cut the grain boundaries of calcite (ca).

Note reaction-rims of gummite-like material developed around the uranothorianite crystals where they abut against calcite. Specks of unidentified material of high reflectivity are associated with these reaction rims.

Polished section.
Ordinary light X 80.

Fig. B. Euhedral crystal of uranothorianite (grey) in magnetite (white). Note pitted appearance of magnetite.

Polished section.
Ordinary light X 58.

Fig. A.

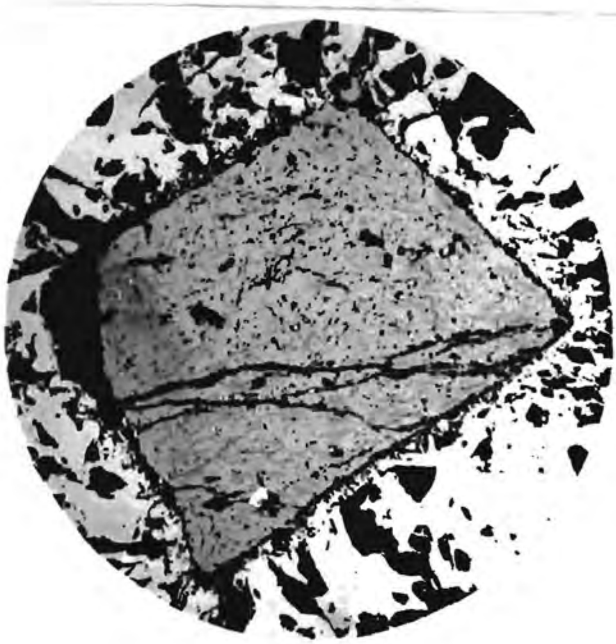

Fig. B.

Plate XXXI

Plate XXXII

Fig. A. Fragments of interstitial uranothorianite replacing calcite. Gangue is calcite and apatite. Note inclusions of apatite.

Polished section.
Ordinary light X 52.

Fig. B. Pyrrhotite (ph) replacing calcite (ca). Inclusions of apatite (a) occur in the pyrrhotite. The pyrrhotite and gangue is veined and replaced by valleriite (black).

Polished section.
Ordinary light X 15.

Fig. A.

Fig. B.

Plate XXXII

Plate XXXIII

Fig. A. Lamellar twinning in pyrrhotite. Veins of valleriite (black) can be seen replacing pyrrhotite.

Polished section.
Nicols X 100.

Fig. B. Pentlandite (pe) in chalcopyrite (chp). Note high relief of pentlandite, due to superior hardness. Irregular fragments of magnetite (grey) in calcite are visible on the right.

Polished section.
Ordinary light X 100.

Fig. A.

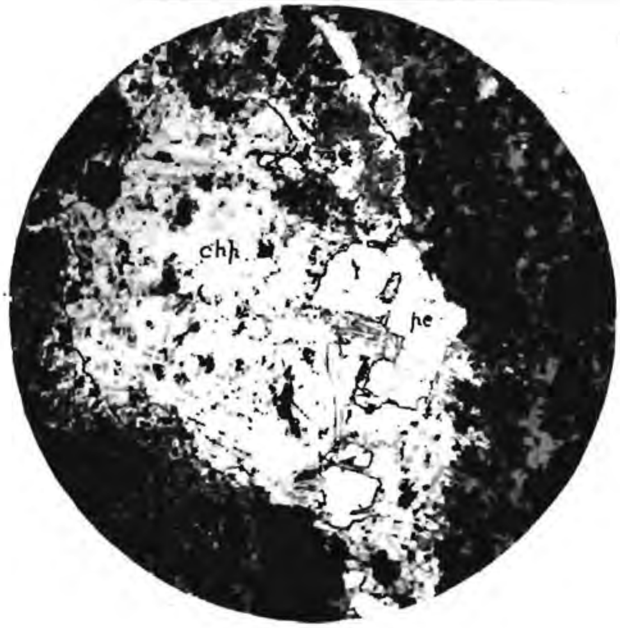

Fig. B.

Plate XXXIII

Plate XXXIV

Fig. A. Ramifying veinlets of valleriite (grey) replacing magnetite (white) along irregular fractures.

Polished section.
Ordinary light X 15.

Fig. B. Intergrowth of chalcopyrite (chp) and bornite (bo) showing mutual relations. The chalcopyrite encloses a cubanite (cu) residual. Note calcite (black) replacing bornite and chalcopyrite. Magnetite (ma) is visible at bottom right.

Polished section.
Ordinary light X 40.

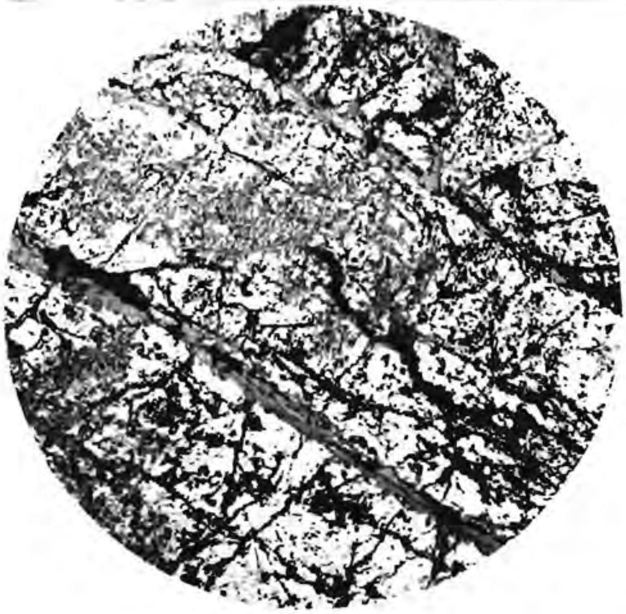

Fig. A.

Fig. B.

Plate XXXIV

Plate XXXV

Fig. A. Cubanite (cu) residual associated with chalcopyrite (chp). Grey is bornite, black is calcite. Enlargement of centre of plate XXXIV, Fig. B.

Ordinary light X 95.

Fig. B. Brecciated carbonate (grey) healed by chalcopyrite (white).

Polished section.
Ordinary light X 12.

Fig. A.

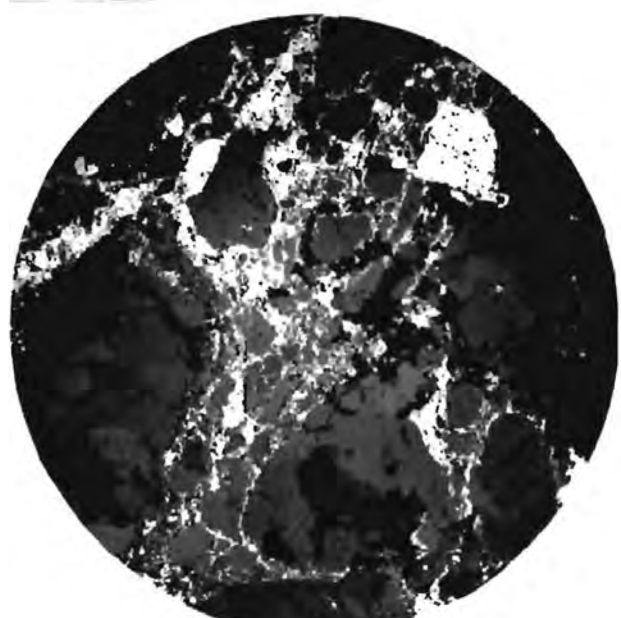

Fig. B.

Plate XXXV

Plate XXXVI

Fig. A. Brecciated carbonate (white) healed by chalcopyrite (black).

Thin section.
Ordinary light X 33.

Fig. B. Ramifying veinlets of chalcopyrite (black) replacing biotite (b) and calcite (ca). Note strained appearance of biotite plates.

Thin section.
Ordinary light X 35.

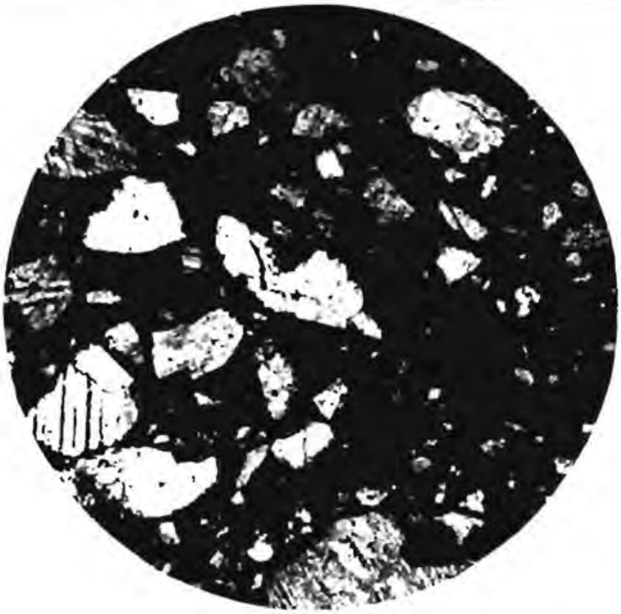

Fig. A.

Fig. B.

Plate XXXVI

Plate XXXVII

Fig. A. Chalcopyrite (black) replacing calcite (grey) along cleavage traces.

Thin section.
Ordinary light X 38.

Fig. B. Bornite (bo) replacing gangue (dark). Note exsolution lamella of chalcopyrite (white) in the crystallographic planes of bornite. Magnetite (m) is visible to the left.

Polished section.
Ordinary light X 17.

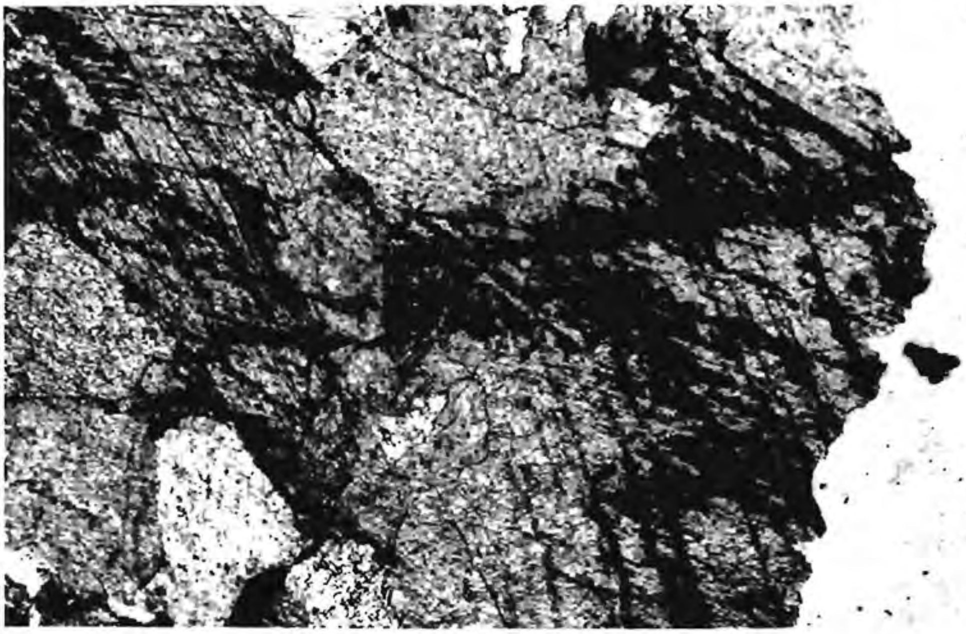

Fig. A.

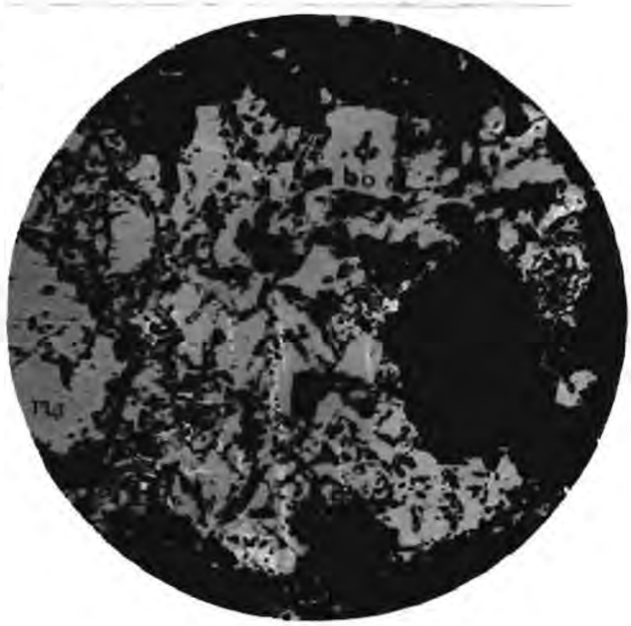

Fig. B.

Plate XXXVII

Plate XXXVIII

Fig. A. Grating texture of bornite (dark-grey) developed in the crystallographic planes of chalcopyrite (light grey). Note displacement of bornite lamellar probably due to, or subsequent to, localised tension set-up during unmixing.

Polished section.
Ordinary light X 100.

Fig. B. Bornite (grey) replacing chalcopyrite (white) from a fracture and diffusing along cleavage planes. The fracture is filled with magnetite (ma), valleriite and calcite. Valleriite and calcite both appear black. Note pitted appearance of magnetite.

Polished section.
Ordinary light X 100.

Fig. A.

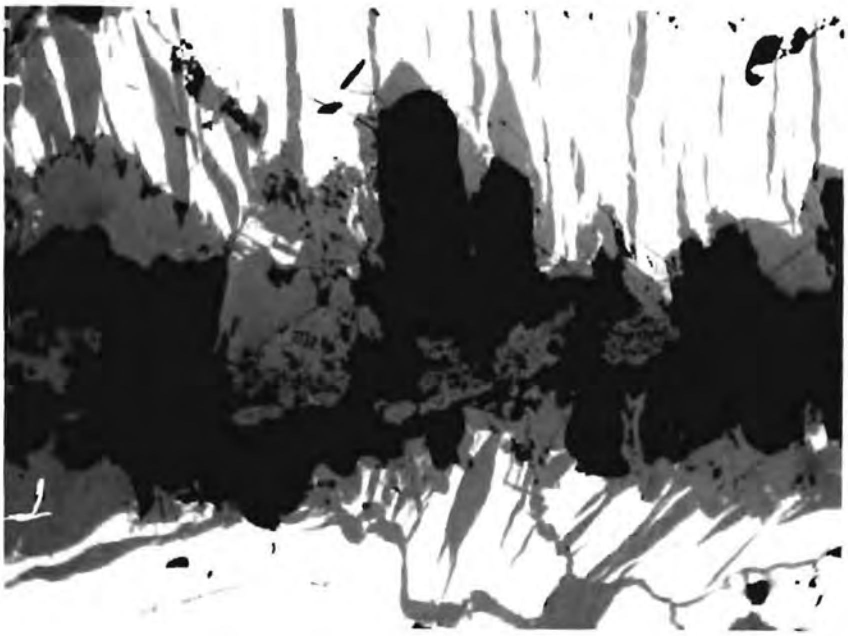

Fig. B.

Plate XXXVIII

Plate XXXIX

Fig. A. Replacement veins of chalcocite (white) in magnetite (grey). The magnetite and gangue (light-grey) is replaced by valleriite (black).

Polished section.
Ordinary light X 15.

Fig. B. Etch with HNO_3 on above chalcocite vein to reveal the parallel etch-cleavage of very fine-grained hypogene chalcocite.

Polished section.
Ordinary light X 2000.

Fig. A.

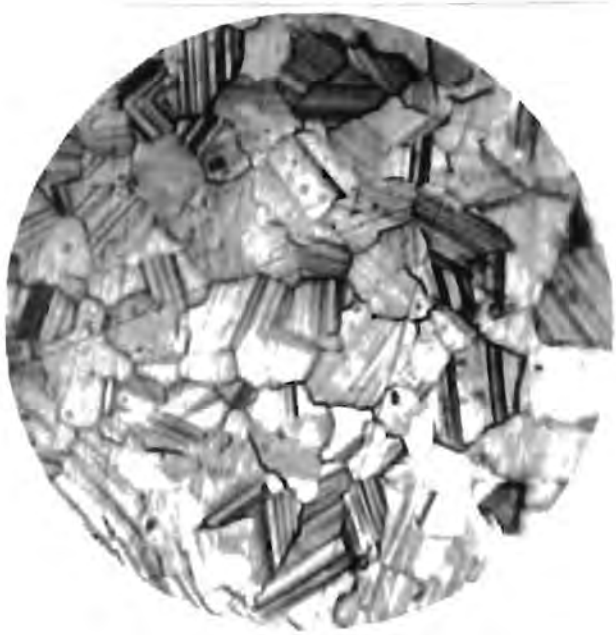

Fig. B.

Plate XXXIX