# THE PETROLOGY

# OF THE

# KIMBERLITES

# AT THE

# PREMIER (TRANSVAAL)

# DIAMOND MINE,

# SOUTH AFRICA.

by

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A thesis submitted to the Faculty of Graduate Studies in partial fulfilment of the requirements for the degree of Doctor of Philosophy in the Department of Geological Sciences, McGill University.

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# CHAPTER I

## INTRODUCTION

### Location and Accessibility

The Premier (Transvaal) Diamond Mine is situated at the village of Cullinan, approximately 20 miles E.N.E. of Pretoria, the administrative capital of the Union of South Africa. It lies at an elevation of 4,722 feet above sea level.

A paved highway connects Cullinan with Pretoria, and a spur-line, runs from the village to the Pretoria-Lourenco Marques railway.

### History

It was more than 20 years after the initial discovery of the Kimberley diamond "pipes" in 1871 in the Cape Colony that Thomas Cullinan discovered the occurrence of diamondiferous "yellow ground", which was later to be known as the Premier (Tvl.) Diamond Mine.

Some of the local inhabitants tell the following story about the discovery. The farmer Prinsloo, who originally owned the farm Elandsfontein, was opposed to any prospecting on his property. Thomas Cullinan was determined, however, to obtain some of the "yellow ground" (weathered kimberlite) for testing purposes. He was convinced that the alluvial diamonds found along the stream on the farm Beynestpoort originally came from the slight depression amongst the hills on Elandsfontein.

Trekking with his ox-drawn waggon, he stopped overnight on this farm and one of his oxen conveniently happened to die. He got permission to bury it and so managed to load some of the badly wanted earth on his waggon. He washed this material and the diamonds he found proved his belief. The farm was later purchased and the total sum paid in gold sovereigns. After very systematic testing, the presence of a diamondiferous kimberlite pipe was proved.

The Premier (Tvl.) Diamond Mining Company was registered on December 1, 1902, with a capital of £80,000, and mining operations started in earnest.

Except for a short temporary shut-down, during a part of the 1914-18 war, open-pit operations were continuous until March, 1932, when the mine closed for a prolonged period. At this time parts of the open-pit had reached a depth of 610 feet.

After fourteen years of inoperation, unwatering of the pit was started in 1946, and the preparation for underground mining was commenced.

Future operations are dependent on the state of the diamond market and world conditions.

## General Statement

The geological mapping of the Premier Mine was part of the general mapping, and sampling programme planned for various diamond mines by the Anglo-American Corporation of South Africa, Ltd.. The initial, and important, part of the work, the mapping of the open pit and parts of the 610-foot level, was done by A. E. Waters and C. G. Stocken, to whom, and especially to the latter, all credit is due for the recognition of the several varieties of kimberlite.

The underground geological mapping was done by the writer during the period January to July, 1948, while in the employ of the Anglo-American Corporation. Mapping was done on the 610-, 660-, 710-, 760-, 810-, 845-, 890- and 1060-foot levels, where development work had been completed prior to, or was being carried on during, this period. In the course of the mapping, both walls of all tunnels were inspected, and the various features, contacts, etc., observed were located from mine survey pegs. All the geology was plotted on mine maps scaled at 1:1000 (1 inch = 83.33 feet).

Most diamond mines are very dusty due to the practice of drilling "dry" in kimberlite. Premier Mine is no exception and the dusty nature of the walls, and the absence of water for washing them down, does not facilitate mapping. By chipping the walls every few feet, and inspecting the exposed surfaces, contacts could generally be located, but smaller features such as inclusions were undoubtedly often overlooked.

No mapping was done in the southeastern part of the mine as there had been no development work there since 1932. The results of the mapping by Waters and Stocken in that part of the open pit have been included in the map of the 610-foot level that accompies this thesis.

The laboratory investigations were carried out in the Department of Geological Sciences of McGill University.

Some work was done during the 1948-49 and 1949-50 sessions but most of the research was completed during the 1950-51 session. The results of the work carried out during the 1948-49 session was submitted as a thesis in partial fulfilment of requirements for the degree of Master of Science. The more detailed work, which followed, forms the basis for the present thesis. It included the study of numerous thin sections, polished sections, and crushed minerals, as well as heavy mineral concentrations and stain and chemical tests. A certain amount of spectroscopic work with the Vreeland spectroscope was also undertaken.

## Purpose and Scope of the Investigation

The mapping of this kimberlite occurrence was undertaken to trace the distribution of the various types of the rock. These types will eventually be sampled to determine any variation in diamond content. If such a variation exists, and it proves to be of economic importance, selective mining may be resorted to, if found practicable.

The laboratory investigation was undertaken for various reasons. As far as known, no systematic and detailed study of the various kimberlites of the Premier Mine has previously been carried out, although it was known, long before this present work was started that several types occur in the mine (Wagner, 1914, p. 95).

It was hoped that a thorough investigation might clear up some of the many outstanding questions regarding the genesis, of the kimberlite and its magmatic and subsequent history.

While the work was not primarily planned to throw light on the origin of diamonds, this problem, too, was kept in mind.

## Acknowledgments

The writer in indebted to various persons, without whose kind assistance it would have been either impossible or at best very difficult to complete this work. Thanks are due to the following:

Dr. J. A. Bancroft, consulting geologist to the Anglo-American Corporation of South Africa, Ltd., who kindly gave permission to use the maps and notes compiled by the writer during the time he spent at the Premier Mine.

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# CHAPTER II

# REGIONAL GEOLOGY AND STRUCTURE

## Regional Geology

Superficially examined, the problem of a kimberlite pipe or volcanic neck seems to be of a localized nature, due to its lack of relationship with the surrounding geological formations. Usually, then, only the formations coming in direct contact with the kimberlite are described. In areas such as the Cape and Orange Free State Provinces of South Africa, where the kimberlite pipes occur in nearly flat-lying Karroo strata, this practice is partly justified.

In the Pretoria district, this cover of younger Karroo rocks has largely been removed and the older formations are clearly displayed. Due to the distribution and the inclined nature of the strata, it becomes possible here to trace some of the inclusions, found in the kimberlite, back to their probable source. For this reason, and also because of some structural features later to be examined, a seemingly unnecessarily large territory is here included in the description of the regional geology.

The Premier Mine is situated on the eastern edge of the Pretoria map-sheet of the South African Geological Survey. This fact proved to be unfortunate, as the adjacent sheet is now out of print and no copy was available to the writer. Information for this area had to be obtained from other publications (du Toit, 1939; Hall, 1932).

The area to be described lies in the southeastern portion of Sheet I — Pretoria (New Series) of the South African Geological Survey. Most of the information was obtained from the description (Kynaston, 1929) accompanying the map.

The following geological formations are present in this area:

Recent

Alluvium

Karroo System

| | |
|---|---|
| Ecca Series: | Grits, sandstones, and shales, with coal seams |
| Dwyka Series: | Tillite |

Waterberg System

Sandstone, conglomerates, and shales

Transvaal System

| | |
|---|---|
| Rooiberg Series: | Volcanic beds, shales, sandstones, and conglomerates |
| Pretoria Series: | Shales, quartzites, and volcanic beds; basal conglomerate |
| Dolomite Series: | Dolomitic limestone and chert |
| Black Reef Series: | Quartzites and shales |

Igneous Rocks

Kimberlite occurrences

Volcanic breccia

Syenite, diorite, and allied rocks

Diabase and allied rocks

Bushveld Igneous Complex

Red granite, norite, and granophyre

Older Granite

The distributions of these various formations are relatively simple and can be seen at a glance on the accompanying map.

The Older Granite, which is part of South Africa's "Basement Complex", forms a dome-like structure of which rather less than one-quarter is shown in the southwestern corner of the map.

Overlying the Older Granite, we find the Black Reef Series, followed by the younger series of the Transvaal System. These rocks occur in a broad band, which changes rather abruptly in strike from nearly east-west at Pretoria to northwest-southeast just east of the same city. The beds are all inclined to the north or northeast at angles ranging from ten to thirty degrees. Locally, near faults or in the folded area to the south, the dips may be much steeper. Generally speaking, the inclination is steeper in the vicinity of Pretoria and decreases in amount toward the east where, as a consequence, the outcrop area becomes much wider.

The Transvaal System, here and elsewhere, forms the "floor" of the Bushveld Igneous Complex and is always found dipping under this body of igneous rocks.

The Rooiberg Series of the Transvaal System is represented, by a variety of rock types, on the northern boundary of the area.

Small areas covered by the Waterberg System occur to the north and southeast of the Premier Mine. While these areas are represented by isolated patches on the map, they are actually part of a large tract of country covered by these rocks to the north and east of the map-area. Originally, this system must have covered a larger area, as we find inclusions of the typically red Waterberg sediments in the Premier Mine. This point will again be referred to in the chapter on the geology of the Premier Mine.

The Karroo System, which once completely covered this whole area, has been largely removed by denudation and is now represented by isolated outliers of nearly flat-lying glacial and other sediments.

Rocks of the Bushveld Igneous Complex occur in the northwestern part of the area. For a clearer picture of the relationship of this complex with the other formations of the map-area, it is best to refer to the smaller scale structural map (following page 11).

Several intrusive bodies, apart from the main mass of the Bushveld Igneous Complex, also occur in this area. These include diabase dykes and sills, which are specially numerous in the shales of the Pretoria Series. Most of these parallel the bedding of the sedimentary rocks they intrude, although some have a vertical attitude.

A few minor intrusions of syenite and allied rocks, probably belonging to the Bushveld Igneous Complex, occur at various places.

A total of four kimberlite occurrences are found in the map-area. These are part of a group of eleven known occurrences in the general region whose locations are indicated by a full circle on the structural map (following page 11). With the exception of the dyke on the farm Franspoort, all are believed to have the form of pipes.

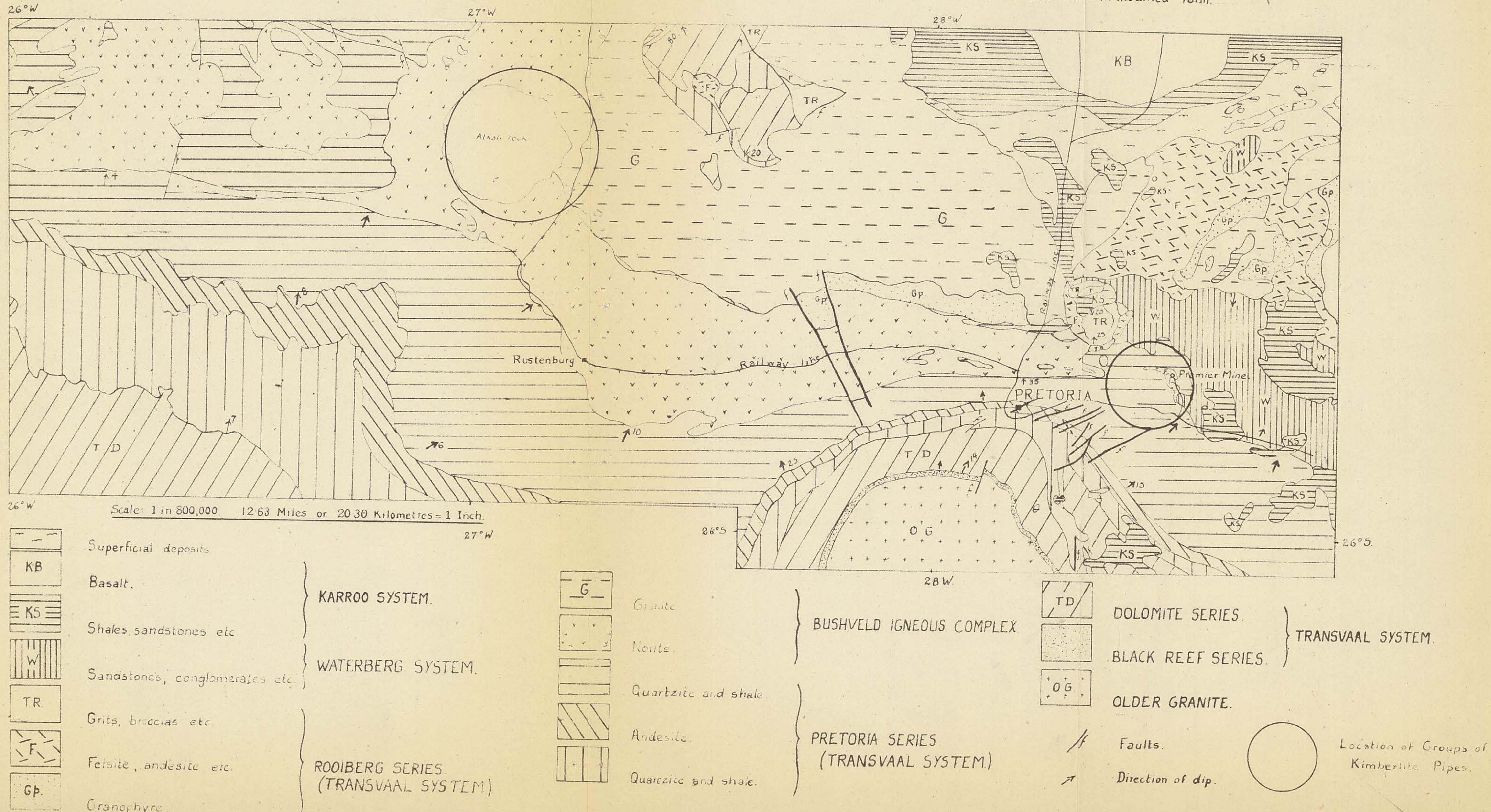
Elsewhere, the kimberlite pipes are known to be of Post-Karroo age, and the same age is assumed for these, occurring in the Pretoria district.

## Structure

When inspecting the relationship of a single occurrence of kimberlite with the structures in the immediate vicinity, no reason for the particular placement of the pipe can be found in most cases. Some pipes are situated on igneous contacts or fracture zones (Williams, G. J., 1939); others are found arranged along a definite line indicating some deep-seated structural control (Wagner, 1914, p. 8).

# MAP SHOWING LOCATION OF GROUPS OF KIMBERLITE PIPES IN THE PRETORIA AND RUSTENBURG DISTRICTS

Adapted from Mem. 28 S.A. Geol. Surv. in modified form.



Considering the probable deep-seated origin of kimberlite, it is clear that deep-lying structures may play an important role in controlling or determining the particular location where an eruption or intrusion will take place. In the Cape and Orange Free State Provinces, such structures can only be assumed, because of the covering of nearly horizontal strata.

In the Pretoria district, this cover has been largely removed and various structures are displayed which may give us a more solid basis for speculation.

Individual pipes in this area are scattered around in a seemingly haphazard manner and their positions do not show the influence of any particular local structures. When we take a broader view, however, and consider the location of the pipes as a group, rather than as individuals, in relation to the major structures of the region, the resulting picture is more systematic.

The group of kimberlite bodies of the Pretoria district occur to the northeast of a series of faults, which have displaced portions of the Pretoria Series. A large number of these faults, which are of Pre-Karroo age and consequently older than the kimberlite pipes, seem to converge on the area of kimberlites. The kimberlites are also situated on a broad fold in the Transvaal System.

A similar relationship between structure and kimberlite occurrences exists in the Rustenburg area, west of Pretoria, where a group of pipes occur to the north of a broad fold in the

Transvaal System.

This particular arrangement is suggestive of some structural control over the eruption of the kimberlites.

The lack of control by local structures is easily explained when it is realized that in its upward advance, the first kimberlite magma reached only to a certain horizon below the surface (as at that time), and that the upper zones of the pipe were shattered by gaseous explosions, which would not show a great tendency to be controlled by structures that did not extend to great depth.

# CHAPTER III

## THE GEOLOGY OF THE PREMIER (TRANSVAAL) DIAMOND MINE

### Previous Work

In 1904 Hall published a short article on some of the diamond deposits of the Transvaal, in which he mentions the Premier Mine briefly.

In 1911 Wagner published a more complete study of the kimberlite occurrences of the Pretoria district, and more information is given on the Premier Mine. Much of this is repeated in the same author's, "The Diamond Fields of Southern Africa", where he distinguishes twelve different varieties of "blue ground" (kimberlite) in the Premier Mine. He gives brief descriptions of all these, together with a sketch-map, on which the locations of the several varieties are indicated by numbers. However, the boundaries of these varieties are not shown. Wagner also gives three chemical analyses of Premier kimberlite and compares these with wehrlite (olivine-diallage rock).

During the Shaler Memorial Expedition to Africa in 1922, Daly paid a brief visit to the Premier Mine, and in 1925 he published an account of the carbonate dykes which occur in this mine. His views are opposed to those of Wagner, who thought these dykes probably represent replaced kimberlite.

"The Genesis of the Diamond", by A. F. Williams, was published in 1932. This work makes reference to the Premier Mine in a number of places. The author gives a brief description of the various kimberlites and dykes, but no account of the distribution of these rocks. He also supplies a number of chemical analyses of dykes and kimberlites.

Just after the mine re-opened in 1946, Stocken, under direction of A. E. Waters, mapped the open pit and portions of the 610-foot level. His map and short report was not published but was available to the present author, and free use was made of this during his subsequent underground mapping.

In 1949 van Biljon published a paper on the Bushveld Igneous Complex, in which he also compares chemical analyses of some of the Premier dyke rocks with serpentine limestones of the Transvaal System, and of the kimberlites with certain shales of the Pretoria Series. From the variation diagram, which this author supplies, he comes to the conclusion that there is a serial relationship between shales and kimberlites, and suggests that kimberlite may have been derived from the transformation of shale. He also makes the suggestion that the diamonds may have been derived from the carbon or graphite "which seems common in the Pretoria shales".

## Rock Types

Investigation of the geology of the Premier Mine involves the study of the country rocks, inclusions in kimberlite, the kimberlite itself, and replaced kimberlite dykes.

The Country Rock

The only rock to be seen in contact with the kimberlite in the open pit and underground is a grey or red felsitic rock which is part of an intrusive sheet, shown on the regional geological map. Where this rock comes in contact with the kimberlite, it does not show any signs of having been altered by contact metamorphism. Microscopic examination bears out this statement.

On its way to the surface, the igneous material now occupying the pipe must logically have passed through a variety of rock types, and deeper than the present workings we may expect to find all the series of the Transvaal System, as well as older rocks, in contact with the kimberlite. All of these rocks will naturally never be exposed, as they lie beyond the limit of practical mining.

The following table shows the probable depths at which various rock types were traversed by the kimberlite:

| | |
|---|---|
| 0 to 2,000 feet | Felsite |
| 2,000 to 20,000 feet | Pretoria Series, including numerous diabase dykes |
| 20,000 to 23,500 feet | Dolomite Series |
| 23,500 to 23,550 feet | Black Reef Series |
| 23,550 to ? feet | Old Granite |

## Inclusions in Kimberlite

### 1) Derived From Very Deep-seated Formations

This type of inclusion is found in many occurrences of kimberlite and their origin and nature have been widely discussed by many authors.

Usually they consist of large and small, rounded and "polished" boulders of rocks belonging to the peridotite suite as well as some typical eclogites.

Great interest has been centred upon these inclusions and they have been variedly explained as true water-worn boulders (Bonney, 1907), xenoliths, cognate with kimberlite (Wagner, 1914 and Corstophine, 1907), and accidental inclusions (Harger, 1907).

Holmes (1936) has finally proved that they are not cognate or co-magmatic with the kimberlite. He found that the helium-lead ratio of the kimberlite shows it to be of the Cretaceous age, which is that usually assigned to these pipes, whereas that of the inclusions corresponds more nearly to a Precambrian age.

These curiously rounded inclusions are only abundant in a portion of the inner zone of fragmental kimberlite of the Premier Mine. They are found in the open pit and on the 610-foot level, but appear less frequently on the lower levels. This decrease may be more apparent than real, as the very hard "boulders" would be more conspicuous where the enclosing kimberlite has been weathering for a longer time.

None of the available specimens showed the typical mineral assemblage of eclogite, and all of them can properly be classed as peridotites. Whether true eclogites occur at the Premier Mine is not definitely known, as no particular study of these inclusions was made.

Of some interest is the report by Wagner (1914, p. 125) that diamonds and graphite-bearing inclusions of the above type have been found in the Premier Mine. Later (1928) he advanced the opinion that these peridotitic inclusions were probably derived from a deep-seated peridotite layer in the earth's crust.

2) Derived From Known Wall-Rocks

Williams (1932, p. 291) mentions the following rock-types occurring as inclusions in the kimberlite of the Premier Mine: granite, syenite, amphibolite, diabase, and dolomite.

All of these rocks may occur, but only one or two of these types were seen by the author. However, owing to the dusty condition of the tunnel walls, inclusions in the kimberlite must frequently have been overlooked during the present mapping.

Fragments of recrystallized limestone were found in the outer zone of fragmental kimberlite. Numerous inclusions of a soft and very fine grained rock, now largely serpentinized and of a dull greenish appearance, were also found in this zone. Due to extreme alteration, the nature of these is not definitely known but it is suspected that they may be fragments derived from the shale members of the Pretoria Series.

Very small fragments, often of microscopic size, of a variety of igneous rocks are also found in the kimberlite in various parts of the mine. Alteration, chiefly serpentinization, has proceeded so far in most cases that the nature of the original rock cannot be determined. They all have an apparently igneous texture, and some definitely have a diabasic texture.

Limestone fragments are also found in the intrusive kimberlites. In contrast to similar inclusions found in the fragmental kimberlite, these are all invariably highly metamorphosed. This important point will be discussed later.

All these limestone fragments have evidently been derived from the underlying Dolomite Series, as no other limestone or dolomite beds are known from the portion of the Transvaal System through which the kimberlite now extends.

3) <u>Derived From Overlying Formations, Now Removed</u>

A striking, but not unique, feature of the Premier Mine is the colossal inclusion of red Waterberg quartzite and conglomerate which divides the mine into two distinct portions.

The attitude of this formation was likened by Dr. Waters (personal communication) to that of a magazine tossed into a rather small waste-basket, with the consequent bending and opening of the pages. This general appearance is evident on the map of the 610-foot level.

The whole mass dips steeply to the northwest, and portions of it have been encountered as deep as the 1,060-foot level. Adjacent to the main body, rubble zones of varying extent can usually be found. These zones, which also appear independent of the main mass, especially southeast of the latter, consist of large and small blocks of Waterberg rocks in a matrix of kimberlite.

The Waterberg System does not occur in the immediate vicinity of the mine; the nearest occurrence is a small outlier about three miles to the north. The inclusion of rocks of this system in the Premier Mine kimberlite thus affords proof that these rocks cover a smaller area at present than they did during the eruption of the kimberlite. Inclusions of the same kind have, moreover, been reported from other kimberlite occurrences of the Pretoria district (Wagner, 1914 p. 22).

Apart from this evidence of previous wider distribution, the presence here of Waterberg rocks also attests to the explosive nature of the initial eruption which formed the pipe in which the kimberlite was emplaced.

Kimberlite

Before the kimberlites are described, a word about the colour of these rocks may not be out of place. Various colours such as green, bluish-green, greenish-grey, bluish-black, as well as faint purple, are found. Not all of these colours can be adequately explained. However, it is apparent that the various shades from greenish-grey to bluish-black are, to some extent, due to the presence of certain alteration products. The serpentine found in the kimberlite varies in colour from nearly black to almost yellow. This mineral, mixed with different quantities of antigorite and talc, may cause all the various colours to appear.

The purple colour was noted in the Micaceous kimberlite, where it may be due to the presence of minute flakes of mica.

The kimberlites of the Premier Mine can be divided into two main groups, according to their mode of emplacement:

1) Fragmental kimberlite
2) Intrusive kimberlite

## 1) Fragmental Kimberlite

Two groups of fragmental kimberlite are present, an outer and an inner zone, partly separated by a series of intrusive kimberlites, which are roughly crescentic in plan.

## A) The Outer Zone of Fragmental Kimberlite

The outer zone of kimberlite breccia or agglomeratic tuff can in turn be divided into three parts on the basis of general appearance.

During the initial mapping, Stocken separated these three members, and later, during the underground mapping, the same practice was followed. Subsequent microscopic work did not reveal any characteristics which could be used to distinquish the three varieties, except, to a certain extent, the degree of alteration. The following field names were applied to the three members, and for ease of description these names are retained here: Normal, Intermediate, and Blue-grey kimberlites. The Normal kimberlite is the outer, and the Blue-grey the inner, member.

### i) The Normal Kimberlite

The choice of this name is rather unfortunate and it must not be taken to signify that this is the normal type of kimberlite. Several varieties of kimberlite occur and it would be impossible to say which is "normal".

The Normal kimberlite is a dull, bluish-grey to greenish-grey rock with a fragmental appearance (Plate 1, Figure 1).

Individual minerals are normally not easy to see due to the advanced stage of alteration of this rock. Ilmenite and hypersthene grains are the exception. These appear as purplish-black and greenish-grey grains, respectively, in most hand-specimens. Also present, but rarely seen in hand-specimen, are grains of green chrome-diopside and flakes of phlogopite.

Very conspicuous and invariably present are inclusions of foreign rock. Except for rocks belonging to the Waterberg system, these xenoliths are usually of small size, but they range in diameter from a fraction of an inch to several inches. The largest percentage consist of small fragments of fine grained material, usually of a dull greenish colour, of which some have been identified as shale. The most likely source of these is the underlying Pretoria Series, which contains several thick shale members.

The Normal kimberlite is the only type that makes contact with the felsitic "wall" rocks in the part of the workings now exposed. It is also the only kimberlite found southeast of the so-called "floating reef" of Waterberg rocks.

The contact with the country rock, where observed, is always extremely sharp, and usually it is slickensided, sometimes with the development of a small amount of gouge.

Du Toit (1906, p. 155) accounted for these slickensides by postulating a large amount of upward expansion in the kimberlite during the process of serpentinization. This theory of expansion is firmly embedded in the literature concerning kimberlite. It is, however, not necessary to assume that minerals, such as olivine and pyroxene undergo expansion on serpentinization (Hess, 1933).

The original explanation given by Daubreé (1890) is probably more correct. During his experiments on the formation of diatremes, he found that the sides of the small holes pierced in the tested rocks were smoothed and slickensided by the fast moving gases and material.

The Normal kimberlite was most likely emplaced as a breccia or agglomeratic tuff by a gaseous explosion, and during this eruption the walls became smoothed and slickensided.

While the Normal kimberlite makes sharp contact with the "wall" rocks, the contact with the Intermediate, and in places the Blue-grey, kimberlite, is gradational and usually difficult to map.

### ii) The Intermediate Kimberlite

The transitionary nature of the Intermediate kimberlite is clearly brought out by its appearance. When inspecting a suite of hand-specimens, it is obvious that some may easily be grouped with the Normal, and others with the Blue-grey kimberlite.

When highly altered, this rock approaches the rather featureless Normal kimberlite in appearance. Less altered, it is more like some phases of the Blue-grey kimberlite, with rather prominent, black, waxy pseudomorphs of serpentine after olivine, and a darker greenish matrix.

Foreign inclusions are again plentiful and, in addition to many tiny fragments of altered shale, the rock contains in places some pieces of limestone. The lack of metamorphism of the latter is important and will be discussed later.

Ilmenite and hypersthene are fairly prominent in grains averaging about 5 mm. in diameter. Also present but in very minor amount are chrome-diopside and small flakes of phlogopite.

The Intermediate kimberlite is not continuously exposed in any part of the mine. Whether it forms a continuous zone on any level is thus not known. On the 710-, 760-, 810-, 843- and 890-foot levels it is apparently present as two rudely crescentic zones between the Normal and Blue-grey kimberlites. Contacts with both adjacent kimberlites are all gradational and vague.

The fact that in some of the areas where the Intermediate kimberlite is absent the Normal and Blue-grey types make sharp contact with each other is important, and may have some bearing on the formation of the Intermediate type. This point, together with its appearance and distribution, seems to indicate that the latter is merely a product of the mixing of Normal and Blue-grey kimberlites which took place during the eruption of the Blue-grey kimberlite.

iii) The Blue-Grey Kimberlite

The brecciated or agglomeratic nature of this rock is not as apparent in hand-specimen as it is in thin section. In hand-specimen, it has a marked porphyritic appearance due to the presence of waxy, black pseudomorphs of serpentine after olivine, which are set in a dull greenish to bluish-grey, earthy looking groundmass (Plate I, Figure 2).

Small inclusions of shale and fragments of crystalline limestone are present; the former apparently in lesser amount than in the Normal kimberlite.

Ortho-pyroxene appears more plentiful than in the Normal kimberlite, while ilmenite, though present, seems less prominently displayed. Chrome-diopside and phlogopite are again present in minor amount.

Where more altered than usual, this rock takes on a dull bluish colour and loses its outstanding porphyritic appearance. In this case, the only minerals visible are bright grains of ilmenite and altered pyroxene.

The Blue-grey kimberlite occurs as a nearly cylindrical zone, from 10 to 170 feet wide, northwest of the Waterberg quartzite. It is surrounded by the Normal and Intermediate members of the outer fragmental kimberlites.

In the open pit on the northeast side, where this kimberlite could be expected, the possible area of outcrop is covered by rubble and by blocks fallen from the side of the pit.

As no underground exposures were available in that area either, it is not known whether the zone of Blue-grey kimberlite is actually circular in plan.

On the outside, this zone makes contact with the Normal and Intermediate kimberlites. The contact with the Intermediate is everywhere gradational. In a few places, especially on the north side, this type makes quite sharp contact with the Normal kimberlite. When plotted on a map, the trace of this outer contact is conspicuously even. There are two possible explanations for this.

a) Minor irregularities may have been overlooked, due to the gradational nature of the contact.

b) It is exactly the kind of contact one would expect to find if the Blue-grey kimberlite was emplaced as an agglomeratic tuff by some gaseous explosion. (In this respect, the smoothness of the contact between the Normal kimberlite and the country rock should be noted.)

Along the inner margin, the Blue-grey kimberlite comes, variously, into contact with the oldest member of the intrusive kimberlites, and the eastern member of the inner zone of fragmental kimberlites.

The contact with the Blue-black kimberlite is always gradational but generally easier to map than the outer boundary. Part of the vagueness is probably due to the fact that highly altered Blue-black kimberlite may approach the Blue-grey kimberlite in general appearance, although the latter is usually lighter in colour.

The irregularity of the inner contact contrasts sharply with the general evenness of the outer contact.

## B) The Inner Zone of Fragmental Kimberlite

The inner zone of fragmental kimberlite is arranged around the No. 1 Blue Shaft in the northwestern part of the mine. It can be divided into two parts. This division is based on the difference in appearance, which is rather conspicuous.

The two members lie approximately east and west respectively, of a north-south line through the No. 1 Blue Shaft and for convenience they will be termed the Eastern and the Western fragmental kimberlite.

### i) The Western Fragmental Kimberlite

Typically, this rock is pale bluish to bluish-grey in colour. It is very dull in appearance, and is soft and porous but rather difficult to break.

Individual mineral grains are not at all conspicuous although some ilmenite and a yellowish, very soft alteration product, most likely of olivine, appears (Plate II, Figure 1).

Conspicuous pale-purplish to pale-bluish fragments occur as inclusions in most exposures of this rock type.

These have been thoroughly altered and although they may represent shale fragments, this is by no means certain.

On most levels, this fragmental kimberlite occurs as a number, usually three, more or less lens-shaped areas. These areas are separated from each other by intrusive kimberlite and replaced kimberlite dykes.

From the evidence available at present, it would appear that the rock occupies progressively smaller areas as it is followed downward on the different levels.

It makes sharp contacts with the Blue-black kimberlite, while contacts with the other types are generally less sharp.

While the distribution of the Western fragmental kimberlite is fairly regular on most levels, the 1,060-foot level forms an exception. On this level the rock is present in only one area and this is too far to the northwest to correspond in position to the occurrences on the higher levels. This apparently anomalous position and disappearance of the rest of this kimberlite is very clear, when inspecting a glass model or superimposed maps of the mine (See Figure 1). This distribution can be explained only by assuming that here the fragmental kimberlite was replaced, in part, by the upwelling of the Micaceous and Carbonate-rich kimberlite. It is apparently younger than the Blue-black kimberlite, with which it makes sharp contact in places.

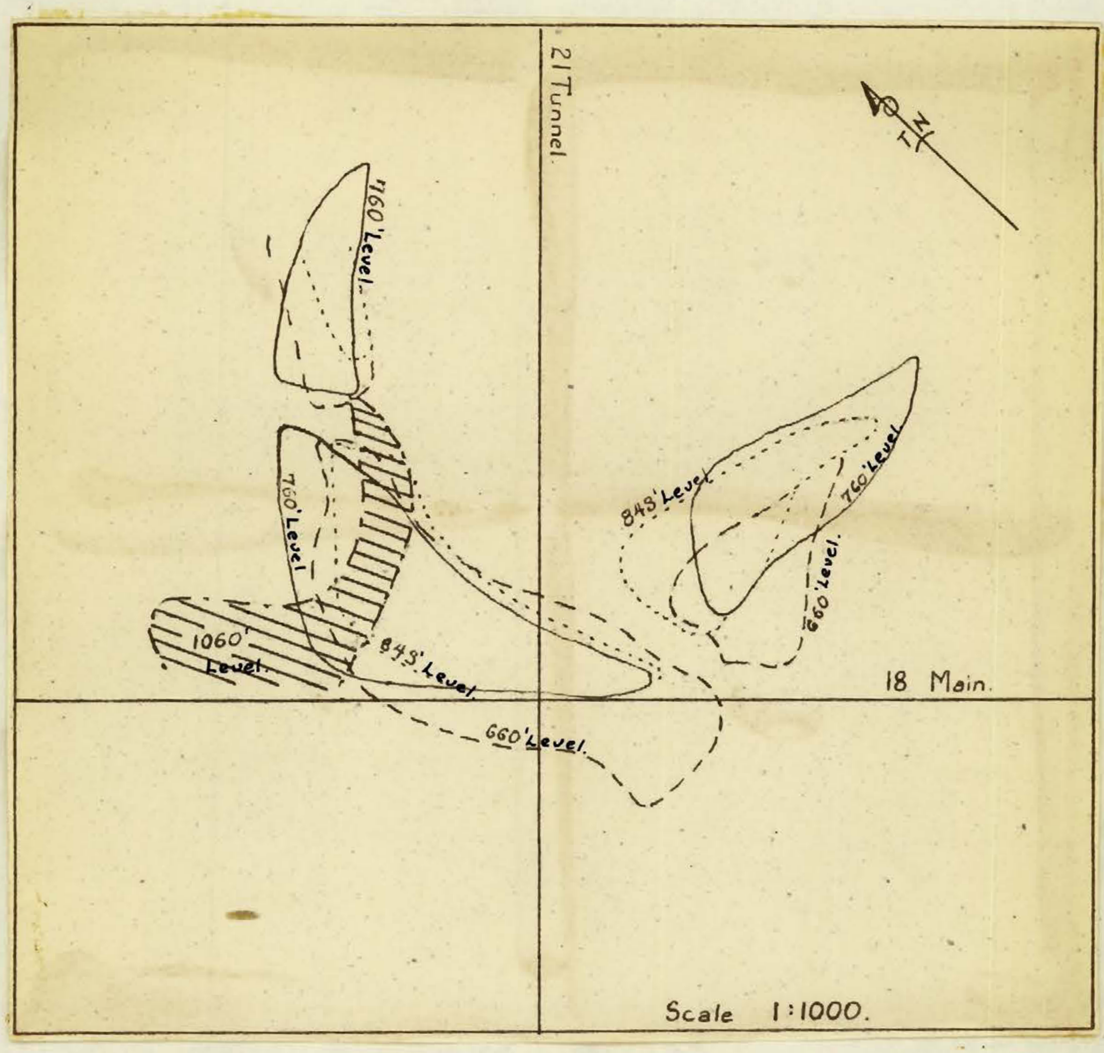



Figure 1.

Superimposed plan, showing the distribution of the Western fragmental kimberlite.

ii) The Eastern Fragmental Kimberlite

This type is a dull greenish-grey rock with dark pseudomorphs of serpentine after olivine up to 25 mm. in diameter, distributed through a dull matrix. Ilmenite, in large, bright, rounded grains is also conspicuous. The grains of this material may be as much as 20 mm. in diameter and are much larger than those generally found in the other kimberlites (Plate II, Figure 2).

Inclusions of other rock types are not very conspicuous, with the exception of the rounded "boulders" of peridotite, previously mentioned. A large inclusion of the Blue-black kimberlite was also found on the 890-foot level.

This kimberlite is exposed in the open pit, west of the old inclined haulage. Underground, it appears east of No. 1 Blue Shaft along the 24 Main (one of the northwest-southeast tunnels). On the 710-foot and 810-foot levels it also appears in tunnel 18, north of 24 Main, and on the 760-foot level along tunnel 21, north and south of 24 Main.

Where we would expect it to appear on the 1,060-foot level, we find, instead, the intrusive Micaceous kimberlite. It is not possible to say whether this rock extends down as far as the 1,060-foot level.

## 2) Intrusive Kimberlite

The intrusive kimberlites occur in the central part of the northwestern section of the mine. They can be divided in three types: Blue-black, Micaceous, and Carbonate-rich kimberlite.

### A) Blue-Black Kimberlite

When best preserved, the Blue-black kimberlite is a very nearly black rock, and the usual macroscopic constituents of kimberlite are difficult to identify (Plate III, Figure 1). When the rock is slightly more altered, it takes on a very dark green colour, and waxy black pseudomorphs of serpentine after olivine become visible. Of the other usual constituents of kimberlite, ilmenite and chrome-diopside are present, the latter, however, in very minor amount.

In places, the rock contains occasional small inclusions. Due to strong metamorphism, it is difficult to say what these were originally.

The Blue-black kimberlite occupies a fairly wide and irregular zone in the central portion of the northwestern part of the mine. On some levels, it extends as far as No. 9 tunnel and, to the southeast, for more than 100 feet beyond 14 Main. On the south, it continues to just beyond the No. 30 tunnel, where a conspicuous bulge is present in some areas. On the 890-foot level, what appears to be a dyke of Blue-black kimberlite intersecting the Eastern fragmental kimberlite just southeast of No. 24 tunnel in 24 Main is more likely a large inclusion.

Exactly how this kimberlite is distributed east of the No. 1 Blue Shaft is not known, as no exposures were available in that area. North of the shaft, it may extend beyond 32 Main, but on the 760-foot level it pinches out between the Blue-grey and Eastern fragmental kimberlite before it reaches 32 Main.

The contact of this type with the Micaceous kimberlite and the Blue-grey fragmental kimberlite is gradational, while contacts with the members of the inner fragmental zone are, as a rule, relatively sharp.

The rock at the contacts is not visibly metamorphosed, and chilled margins were not observed.

B) Micaceous Kimberlite

When fresh, this variety of the intrusive kimberlite is a very dark rock with a faint purplish tinge. Dark green unaltered, and black serpentinized, olivine phenocrysts are present, as well as some grains of ilmenite (Plate III, Figure 2).

Where this rock is more highly altered, as in the North Blue haulage on the 1,060-foot level, the matrix is mottled green and purple, while the olivine crystals have been converted to green or yellowish soft serpentine.

Inclusions are not prominent everywhere in this rock, but fragments of a dense, very pale greenish material are sometimes present. In the more altered phases of the rock, inclusions of a much darker colour become visible; these, together with some very pale coloured inclusions, are thought to represent metamorphosed fragments of limestone.

The Micaceous kimberlite makes up but a small percentage of the total rock present in the mine. It occurs in fairly narrow zones to the south, southwest, and west of No. 1 Blue shaft. One small lens also occurs northwest of the shaft on the 890-foot level.

In a three-dimensional glass model of the mine, the irregular pinching and swelling of this type is well displayed, and unconnected lenses and columns can be seen. This irregular distribution was difficult to understand before the whole history of the mine was built up from separate pieces of evidence.

Originally, the Micaceous kimberlite had a much wider distribution. Before the larger part of it was partially absorbed by the Carbonate-rich kimberlite, it occupied a fairly large central zone, from which several dykes extended. The subsequent fracturing and absorption by the Carbonate-rich kimberlite was irregular and left isolated lenses and columns of the Micaceous rock in various parts of the mine.

Contacts between this kimberlite and the Blue-black type are gradational, while those with the Carbonate-rich kimberlite are sharp. Gradational contacts were also observed between the mixture of the Micaceous and Carbonate-rich kimberlite and the pure Micaceous kimberlite.

C) Carbonate-Rich Kimberlite

The Carbonate-rich kimberlite is a pale greenish porphyritic rock with yellow or greenish pseudomorphs of serpentine after olivine set in a granular, almost oölitic looking, groundmass. Grains of ilmenite are present, but do not reach large sizes. The other primary minerals of typical kimberlite may be altogether absent, as they are never seen.

Numerous white and greenish-grey inclusions occur in the rock. Usually these show a white corona around clear or turbid calcite.

Clear, round grains of calcite, often measuring more than 5 mm. across, occur independently, scattered through the rock (Plate IV, Figure 1).

From the 660- to the 890-foot level, this kimberlite occurs as a comparatively short dyke with a width of four to twenty feet. It has its greatest development on the 1,060-foot level, where it has been exposed along the South Blue haulage for a length of about 120 feet. It has not been observed on the 610-foot level, where a rock dump now covers the area where it may outcrop.

This kimberlite makes sharp contact with the Micaceous and the Blue-black kimberlite.

Besides this relatively pure kimberlite, there is in the mine a large extent of rock which represents an intimate mixture of the Micaceous kimberlite and the Carbonate-rich type. This "mixed" zone is occupied by a porphyritic-looking rock which may show all gradations from dark Micaceous kimberlite to pale Carbonate-rich kimberlite. That the mixture is not merely mechanical is clear from the absence of clearly defined fragments of the Micaceous kimberlite.

The "mixed" zone has its greatest development just southwest of No. 1 Blue shaft. Narrow zones of this rock also flank the replaced kimberlite dykes in many parts of the mine and consequently the Micaceous kimberlite, and later the "mixed" rock, must originally have appeared as dykes in a number of places.

D) Replaced Kimberlite Dykes

These dykes will be described separately in Chapter VI.

# CHAPTER IV

## PETROGRAPHY AND MINERALOGY OF THE KIMBERLITES

Dunn was apparently the first person who realized that the rock in which the diamonds occur in South Africa is igneous in nature (Dunn, 1874). In 1886, H. Carvill Lewis first applied the name "kimberlite" to this rock, which he found to be a "porphyritic, volcanic peridotite of basaltic structure". He further clearly distinguished kimberlite, kimberlite breccia, and kimberlite tuff (Lewis, 1897).

Bonney was always opposed to this idea and maintained that kimberlite was in the nature of a fragmental rock (Bonney, 1897). Even as late as 1907, he spoke about the "supposed" kimberlite magma.

In 1909, Wagner classified kimberlite into two varieties, which differ both in composition and structure:

a) A basaltic variety, poor in mica (the kimberlite of Carvill Lewis)

b) A lamprophyric variety, rich in mica

He further stated (1914, pp. 78, 79) that, in the basaltic variety, phlogopite may occasionally form phenocrysts, but never "enters largely into the composition of this groundmass" (of the kimberlite).

On the other hand, the lamprophyric kimberlite, according to Wagner (1914, p. 79), has a "holocrystalline or hypocrystalline groundmass, of which phlogopite is the dominant constituent".

This classification of Wagner's has been generally accepted and is the one used by du Toit (1929) and Williams (1932).

Wagner further classified the kimberlites of the Pretoria district with the basaltic kimberlites (Wagner, 1914).

This classification is no longer justified in the case of the Premier Mine, as at least one definitely micaceous kimberlite has been found and the indications are that all the kimberlites here may originally have had a micaceous groundmass, similar to that of the lamprophyric kimberlites.

The kimberlites of the Premier Mine contain various combinations of the following minerals.

| Primary Minerals | Secondary Minerals |
|---|---|
| Olivine | Serpentine |
| Phlogopite | Antigorite |
| Enstatite | Talc |
| Hypersthene | Chlorite |
| Diopside | Magnetite |
| Perovskite | Rutile |
| Ilmenite | Perovskite |
| Magnetite (?) | Sphene |
| Garnet (?) | Calcite |
| Diamond | |

Metamorphic

Garnet

Clinopyroxene

Of the primary minerals, garnet, phlogopite, and diopside are seldom seen in hand-specimen, and diamond practically never. Perovskite and magnetite occur in grains that are never larger than microscopic in size.

Of the secondary minerals, serpentine and antigorite are the most abundant, but talc is also important in the outer zone of fragmental kimberlites.

In the descriptions and discussions which follow, the terms "serpentine" and "antigorite" will be used in the sense advocated by Selfridge (1936). This investigator found that there is no justification for dividing serpentine and antigorite into different varieties. He considered that serpentine and antigorite are dimorphous forms of the same compound, $H_4Mg_3Si_2O_9$, which differ from each other only in structure and interplanar spacing, as proved by x-ray analysis.

In order to facilitate the investigation of the kimberlites, it was thought best to start with the best preserved rock and not necessarily describe the several types in the order of their ages. It was found during the study that some features characteristic of one type may be clarified only by the study of another type having a fuller sequence of the same features.

During the investigation of the Premier (Transvaal) Diamond Mine kimberlites, the only type found to contain more or less well preserved primary constituents was the Micaceous kimberlite.

## The Micaceous Kimberlite

This is a porphyritic igneous rock. Irregular and rounded grains of olivine, often more than 10 mm. in diameter, constitute the phenocrysts. These are set in a mass of smaller, often idiomorphic, olivines, tiny flakes of phlogopite, and perovskite grains.

Generally, this rock is altered to a large extent, but in the South Blue haulage on the 1,060-foot level, at least, the rock is practically unaltered. The presence so closely associated of fresh and altered phases of the same rock proved very fortunate, as it made it possible to study the stages of alteration very carefully. The knowledge obtained in this way also made it possible to interpret many of the features in the other kimberlites, of which no unaltered equivalents could be located.

## The Individual Minerals

### Olivine

This mineral makes up approximately 50 per cent of the rock, by volume. It is present in crystals of two distinct types: large phenocrysts which, however, are never idiomorphic, and small, usually idiomorphic, crystals. The contrast in size is well illustrated in Plate V, Figure 1.

Usually, the large grains consist of a single crystal, but a few polysomatic aggregates were seen in the thin sections examined.(Plate VI).

In sections normal to an optic axis, the large grains display a perfectly straight isogyre indicating a very large optic axial angle. The mineral is optically positive. This, together with the optic angle of about 90 degrees, and the specific gravity of less than 3.3, indicates an olivine poor in the fayalite molecule, and in fact, it closely approaches forsterite in composition (Winchell, 1947, part 2, p. 191). The individual grains of the aggregates were found to be slightly more ferriferous.

The small crystals, which are present in far greater abundance than the phenocrysts, are often beautifully idiomorphic. They vary in size but never approach the average size of the phenocrysts. Optically, they are similar to the latter, and presumably they have the same chemical composition.

Wagner (1914, p. 54), Williams (1932, vol. 1), and other authors have previously pointed out that the phenocrysts and the small crystals — both these two groups of olivines, which are present in most occurrences of kimberlite — represent two generations of olivine. The former or "primary transported" olivines of Williams, are believed to have crystallized at depth and to have been carried upward by the still fluid magma. These, then, are the first generation.

The small crystals represent the second generation, and many, if not all, of these probably crystallized out in situ.

No inclusions of other minerals were found in any of the fresh olivines and this, together with the high melting point of olivine, makes it likely that it was the first mineral to crystallize out.

The similarity in optical properties of the two generations is quite remarkable. Normally, an enrichment in the fayalite molecule can be expected in the latest olivines, which presumably formed at somewhat lower temperatures, than the crystals of the first generation.

By this criterion, the polysomatic olivine aggregates would indicate a lower temperature form. If this is correct, it is not clear why these did not crystallize out as individual and separate grains. Actually, these aggregates may represent fragments of an olivine-rich rock which was shattered and invaded by the kimberlite magma.

## Alteration of the Olivine

In the various thin sections of this kimberlite that were examined, the sequence of alteration of the olivine can be clearly followed. This alteration apparently does not differ greatly from that of olivine in general, but, as it gives important clues to the study of the more altered kimberlites, it is fully described here.

The alteration starts and spreads away from the, usually numerous, cracks present in all grains, as well as at the crystal boundaries. Small veinlets of a very pale green serpentine with a birefringence of about 0.005, and which is optically positive with a small optic angle, appear first.

The biaxial positive character would indicate an antigorite-amesite mixture. However, optically positive serpentine is known to exist, and it is believed that the mineral actually is serpentine of this type, with which it agrees in all other characters.

At the same time or possibly somewhat earlier than the development of the serpentine veinlets, patches of a brown fibrous mineral appear in the olivine. These fibres often radiate and individual patches show uneven extinction (Plate VII, Figure 1).

Carvill Lewis (1897, p. 11) and Wagner (1914, p. 56) mention tremolite as an alteration product of olivine. These fibres are not tremolite, however, as the extinction angle of 30 to 40 degrees is too high, and the birefringence of 0.011 is a little too low.

This fibrous mineral is finally replaced by serpentine and the last stage of alteration, in the Micaceous kimberlite at least, is its complete replacement by clear, colourless, or occasionaly faintly pink or green, isotropic or biaxial positive serpentine. The replacement may be such that one uniform grain of serpentine replaces one grain of olivine. Usually, however, this is not the case but, instead, the typical mesh structure of serpentine is found (Plate VII, Figure 2).

Another feature of the alteration of the olivine is the development of needles of rutile. This mineral is not present as an inclusion in unaltered olivine yet in practically every pseudomorph of serpentine there are numerous tiny needles of rutile. These apparently start developing along the serpentine veinlets and later develop throughout the whole grain (Plate V, Figure 2).

The arrangement of these needles is apparently haphazard. None of them show any orientation according to crystallographic directions of the original olivine grain, although such arrangements were found by Lewis (1897, p. 11) and Wagner (1914, p. 55) in other kimberlites.

These rutile needles are probably the result of exsolution. Titanium was probably present in the crystal lattice of the original olivine. There is little difference between the ionic radii of magnesium (0.65) and titanium (0.68) and some titanium may proxy for magnesium. During the alteration, the composition and structure changed and $TiO_2$ separated out as needles of rutile.

Magnetite is rarely present as an alteration product of olivine of either the first or second generation. This corroborates the evidence of the optical data.

The alteration of the polysomatic aggregates, however, liberates a fair amount of magnetite in the form of tiny octahedra. This evidence of the original presence of iron in these aggregates is in agreement with the optical data.

Chromium is also present in the olivine in a minor amount, as proved by spectrographic investigation. This is apparently true of the olivine in all types of kimberlite, as pointed out by Partridge (1934).

## Pyroxene

Primary pyroxene minerals have not been observed in any of the thin sections of the Micaceous kimberlite. If at all present they must be in very minor amount.

## Perovskite

A fair amount of perovskite, as grains and granular aggregates, occur in the rock, making up, as closely as could be established, about 2.7% of its volume.

Some of the grains have obviously been derived from the alteration of ilmenite, because this mineral is always fringed by a border of perovskite, with an average width of

0.03 mm.. A number of the grains may be an original constituent as they occur in idiomorphic and twinned forms.

A typical twinned grain has an ill-defined six-sided outline. That it is built up of twin lamellae is clear from the presence of small re-entered angles (Plate VIII, Figure 1).

In thin section, the grains are brown in colour, and they have extremely low (0.001) birefringence and high refractive index. The twinned grains usually have a very dark, practically opaque, centre whereas the anhedral grains and aggregates are more transparent.

## Phlogopite

The groundmass of the Micaceous kimberlite consists largely of flakes of phlogopite, with an average length of about 0.03 mm..

The flakes are of a pale brown colour and while they are pleochroic, the absorption is much weaker than in biotite.

The majority of the flakes show normal absorption (i.e., strongest absorption when they lie with their length parallel to the vibration direction of the lower nicol). A few flakes, however, show abnormal or reversed absorption. This abnormal phlogopite has been found in other occurrences of kimberlite (Wagner, 1914, p. 58) and it is interesting to find that this type, although very little of it, is present in kimberlite of the Premier Mine.

The phlogopite alters quite readily. Only occasionally is one flake of mica replaced by one flake of chlorite. More often it alters to an aggregate of very tiny pale green flakes, which may be chlorite. The individual flakes are so small, however, that no convincing optic properties could be determined.

This particular mode of alteration makes it difficult to establish whether mica was originally present in a rock of this type. This, too, is probably the reason why Wagner (1914, p. 80) originally classified the kimberlites of the Pretoria district, which include the Premier Mine kimberlites, with the basaltic types. There is some evidence, however, that most of the kimberlites of the Premier Mine originally had a micaceous matrix.

Wagner's mistake, if indeed it was one, is easily understood when it is realized that his original investigation went only as far as 200 feet below the surface, and the rocks exposed there were apparently much more altered than those of, for instance, the 1,060-foot level, which are now available for study.

Ilmenite

In thin sections, grains of ilmenite of varying size can usually be found, although they are never very abundant. The edges usually have an irregular appearance, due to the alteration to perovskite, which has been mentioned earlier (Plate VIII, Figure 2).

This alteration to perovskite apparently took place during the magmatic stage as surfaces of obviously broken grains of ilmenite in the fragmental kimberlites lack this border of perovskite.

Spectroscopic investigation of the ilmenite showed the presence, in addition to titanium and iron, of chromium and magnesium traces of cobalt, nickel, manganese, and calcium. The last named element may represent calcium present in perovskite attached to the ilmenite examined.

Chromium, judging by the presence of even secondary chromium lines in the spectrum of the ilmenite, must be present in fairly large amount.

To find in which combination this element is present in the ilmenite, polished sections of this mineral were examined. Investigation of these sections revealed the presence of only one mineral, ilmenite, and consequently any other elements than titanium and iron present must be incorporated in the molecule $FeTiO_3$ or must be in solid solution.

Wagner (1914, p. 61) gives the following analyses of ilmenite from kimberlite:

| | I | II | III |
|---|---|---|---|
| $TiO_2$ | 53.79 | 49.27 | 49.32 |
| $FeO$ | 27.05 | 29.34 | 27.81 |
| $MnO$ | - | 0.29 | 0.20 |
| $CaO$ | - | 0.13 | 0.23 |
| $MgO$ | 12.10 | 8.87 | 8.68 |
| $Fe_2O_3$ | 7.05 | 11.27 | 9.13 |
| $Cr_2O_3$ | - | 0.63 | 0.74 |
| Total | 99.99 | 99.80 | 100.10 |
| S. G. | 4.436 | 4.556 | - |

I Ilmenite, Kimberley mines

II Ilmenite, MuKorub, South West Africa

III Ilmenite, kimberlite of Elliot county, Kentucky. Contains in addition 0.76% $SiO_2$, 2.84% $Al_2O_3$, 0.19% $Na_2O$, 0.20% $H_2O$ (hygroscopic)

He regarded the ilmenite found in kimberlite as an isomorphous mixture of ilmenite ($FeTiO_3$), geikielite ($MgTiO_3$), and hematite ($FeFeO_3$).

Magnetite

Small, presumably octahedra of magnetite occur in the Micaceous kimberlite, but the distribution of the mineral is erratic and it is absent in most areas.

## Inclusions

Irregular patches of serpentine, garnet, and clinopyroxene, often more than 20 mm. across, occur in the Micaceous kimberlite. Usually, they take the form of concentric arrangements of clinopyroxene and garnet with serpentine in the centre. In places, the garnet and pyroxene, instead of occurring in such aggregates, are scattered through the matrix, as clusters of separate grains.

The garnet is brown or reddish-brown grossularite with a refractive index between 1.72 and 1.73. It occurs as grains, in irregular clusters of grains, and in concentric aggregates with pyroxene, as mentioned above. The most important feature of this mineral is that it is completely isotropic. Merwin (1915) gives 800 degrees Centigrade as the inversion point for grossularite. Below 800 degrees, it is birefringent, but it inverts to complete isotropism above this temperature. The garnet of these metamorphosed inclusions must be regarded, then, as having formed above 800 degrees Centigrade.

The pyroxene form fibrous aggregates, which often occur interstitially between olivine grains, and sometimes in curious circular arrangements (Plate IX, Figure 1). It is colourless in thin section and has been identified as diopside.

None of these partially digested inclusions give positive evidence of what they may have been originally, but the presence of lime-garnet and diopside seems to indicate limestone. Support for this view is found in similarly altered inclusions in some of the other intrusive kimberlites, still to be described.

If these inclusions are actually fragments of metamorphosed limestone, their only possible source is apparently the Dolomite series, through which the magma must have passed in its upward advance.

The presence of isotropic grossularite also indicates that the magmatic temperature must have been above 800 degrees Centigrade.

The absence or apparent absence of primary pyroxene in this rock is curious, in view of the fact that so much mica is present. From a chemical point of view, it seems clear that enough magnesia and silica, as well as other constituents, were present to form pyroxenes.

## The Blue-Black Kimberlite

Like the Micaceous kimberlite, this is a porphyritic rock. The phenocrysts consist of rounded and irregular pseudomorphs of serpentine, after olivine. They often attain a diameter of 5 mm.. They are set in a groundmass in which smaller, often idiomorphic, pseudomorphs of serpentine are prominent.

## The Groundmass

Most writers are inclined to dispose of the groundmass of kimberlite with a few sentences, or one word — "obscure". This is not difficult to understand. Most kimberlites are hydrothermally altered rocks, and many are fragmental as well as altered. A variety of alteration products are present and ordinary petrographic methods fall short, when an attempt is made to differentiate them and determine their nature. Eventually, this knotty and important problem of the groundmass may be solved, perhaps by using such relatively new methods as differential thermal analysis.

Carvill Lewis (1897) and du Toit (1939) were of the opinion that kimberlite originally had a glassy base. Williams (1932, pp. 226, 228), on the other hand, seemed undecided, because he stated that it might have consisted of phlogopite or olivine.

For various reasons, it is not possible to accept the latter of Williams' ideas. The idea of a micaceous groundmass has more appeal, especially if we consider the definite micaceous base of the Micaceous kimberlite, as well as the presence of inclusions of kimberlite with a micaceous groundmass in the fragmental kimberlites.

In the Blue-black kimberlite, we do not find any mica. However, there is some indication that this mineral may originally have been present. In this rock, the groundmass consists now of two types of material: very fine flaky aggregates of, perhaps, chloritic material, and brownish granular material of a slightly higher birefringence and refractive index. Similar chloritic (?) material has been found as an alteration product of phlogopite in the Micaceous kimberlite, while the brown granular material, or something quite similar, was found as an alteration product of mica in the fragmental kimberlites.

This is admittedly very slim evidence for the previous existence of a micaceous groundmass, but no more than this can be said at present.

Secondary carbonate, invariably calcite, appears in the groundmass as irregular grains and patches, where the alteration is well advanced.

## Olivine

No fresh olivine has been observed in this rock, not even in the best preserved specimens from the 1,060-foot level. In some places, at least, the alteration of this mineral has advanced beyond the stage reached by the olivine of the Micaceous kimberlite.

Two generations of olivine were originally present in this rock, and together they made up 40% of the rock by volume.

The first generation is now represented by large anhedral serpentine grains, showing the usual "mesh" structure (Plate VII, Figure 2).

The second generation, which consists of somewhat smaller euhedral or subhedral individuals, have been similarly replaced.

As in the Micaceous kimberlite, the serpentine replacing both generations of olivine is optically positive, with small optic angle.

It was possible to get relatively pure specimens of this serpentine and the powdered mineral was analysed by x-rays*. Use was made of cobalt radiation, filtered through iron, to obtain the interplanar spacings.

The results obtained are compared in the table with two analyses of serpentine (Nos. 1 and 44) given by Selfridge (1936, p. 469).

It will be noticed that lines Nos. 6 and 9 to 13 are missing in McAllister's analysis. The other lines also are weaker than those of the analyses given by Selfridge. It is likely that in his analyses the lines were brought out by longer exposure.

While the spacing of the lines does not agree in all cases, there is clearly a very similar pattern. Selfridge, unfortunately, gives no x-ray analyses for optically positive serpentine, and it is possible that the interplanar spacing is slightly different for the two varieties.

* X-ray analysis by Dr. A. McAllister.

| | Serpentine* B.B. Kimberlite | | Serpentine No. 44 | | Serpentine No. 1 | |
|---|---|---|---|---|---|---|
| Line No. | d Å | Est. I. | d Å | Est. I. | d Å | Est. I. |
| 1 | 5.96 | 7 | 7.379 | 9 | 7.384 | 9 |
| 2 | 4.47 | 2 | 4.573 | 6 | 4.604 | 7 |
| 3 | 3.59 | 7 | 3.656 | 10 | 3.695 | 10 |
| 4 | 2.45 | 7 | 2.477 | 9 | 2.463 | 8.5 |
| 5 | 2.10 | 0.2 | 2.131 | 5 | 2.098 | 2.5 |
| 6 | -- | | 1.721 | 2.5 | 1.724 | 4 |
| 7 | 1.52 | 5 | 1.527 | 10 | 1.528 | 10 |
| 8 | 1.29 | 0.5 | 1.306 | 7 | 1.306 | 6 |
| 9 | | | 1.044 | 0.5 | 1.047 | 1 |
| 10 | | | 0.990 | 4 | 0.992 | 4 |
| 11 | | | 0.877 | 3 | 0.882 | 3.5 |
| 12 | | | 0.762 | 1 | 0.762 | 1 |
| 13 | | | 0.721 | 1 | 0.727 | 1 |

*X-ray analysis by Dr. A. McAllister.

As in the case of the Micaceous kimberlite, rutile needles segregated out during the alteration of the olivine to serpentine. A small amount of magnetite also makes an appearance, thus indicating that the olivine of the Blue-black kimberlite was slightly more ferriferous than that of the Micaceous kimberlite.

In a few places, notably on the 610-foot level, the alteration has proceeded beyond the serpentine stage and antigorite and talc have been formed. The change from serpentine to antigorite usually starts at the mineral boundaries. It is common to find a zonal arrangement of serpentine and antigorite, with the latter forming the outer zone. In the final stage, the whole grain is converted to an aggregate of small fibrous units of antigorite (Plate IX, Figure 2).

Highly birefringent talc may in turn replace the antigorite partially.

A reddish-brown pleochroic material also appears occasionally as an alteration product. Its nature and position in the replacement sequence is unknown.

It was noted in this rock that, when talc is present, the usual included needles of rutile are absent, and, instead, brown grains and aggregates of sphene make an appearance. These may occupy the centre of a replaced olivine grain or may form a "wreath" around its border (Plate X, Figure 1). This change from rutile to sphene will be discussed in a later section.

## Pyroxene

Primary pyroxene is scarce in this rock, and only an occasional grain can be found in thin sections. The mineral is probably present in an amount less than 1% of the total volume of the rock.

Hypersthene - A number of partly fresh grains of faintly pleochroic hypersthene were observed. These are surrounded by a wide reaction rim of obscure material, and may also show incipient conversion to clinopyroxene. Besides the small number of fresh grains, some completely altered grains are present. These are recognized as representing original hypersthene by the presence of the alteration rim. Alteration is usually to optically negative serpentine or to antigorite.

Diopside - A small number of fresh grains of diopside are present in the rock. The grains are anhedral, and do not show any alteration or reaction rim.

## Garnet

Wagner (1914, p. 97) has stated that garnet is scarce in the kimberlites of the Premier Mine. The present study bears out this statement, as no unaltered primary garnet was found. Fragments of material similar to that of the reaction rim, which commonly surrounds garnet in the kimberlites, were seen in a number of slides of the Blue-black kimberlite. These fragments consist of concentrically zoned material. The material of the inner zones is fibrous, brown in colour, and apparently is pyroxene, possibly with some admixed iron hydroxide. These zones may be succeeded by a wide border of magnetite (Plate X, Figure 2).

Perovskite

Perovskite forms approximately 2% (by volume) of the rock. It is present in the usual small grains, which may show twinning. Where talc makes an appearance in the rock, the grains may show partial or complete alteration to sphene.

Ilmenite

A small percentage of ilmenite grains are present. These show the usual peripheral alteration to perovskite.

Spectroscopic and mineragraphic examination showed no significant difference between the ilmenite of this rock and that of the Micaceous kimberlite, previously described.

Magnetite

Tiny octahedra of this mineral are present in fair amount, but it is apparently not a primary constituent as it is always associated with the alteration products of olivine or pyroxene.

By extracting this mineral from the pulverized rock with a strong permanent magnet, it was found that it makes up about 7.5% of the rock, by weight. It is realized that, due to the fact that some of the magnetite grains picked up by the magnet have particles of rock attached to them, the results given by this method are too high, but for comparative purposes this is not a serious matter. Applying this method to the kimberlites, it was found that the Blue-black kimberlite contains five times as much magnetite as the Micaceous kimberlite. As the magnetite is apparently all secondary, this would indicate that the mafic minerals of the Blue-black kimberlite are richer in iron than those minerals of the Micaceous kimberlite.

## Inclusions

The Blue-black kimberlite contains occasional small inclusions which consist variously of serpentine and diopside, or of serpentine, garnet and diopside. The serpentine and garnet (if present) usually form the centre of a rounded structure, around which are arranged laths of pyroxene (Plate XI, Figure 1).

These apparently represent completely metamorphosed fragments of included rock. The presence of serpentine, diopside, and lime garnet indicates that these fragments may originally have consisted of magnesian limestone.

The garnet is a reddish-brown grossularite and, as it is usually completely isotropic, it would indicate a temperature of formation of over 800 degrees Centigrade. The serpentine is the optically negative variety.

A variety of other inclusions occur, but these are usually changed beyond recognition. The exception to this is the occasional rounded fragment of pyroxenite, which usually still contains more or less unaltered minerals.

During the course of this investigation, all the thin sections of kimberlite that could be found in the collection of McGill University were checked. This was done mainly to find out more about the kimberlite dykes, which occur in various parts of South Africa. It was in the course of this rather cursory investigation that some sections of kimberlite from the Schuller Mine attracted attention. The Schuller Mine is a kimberlite pipe, situated approximately four miles south of the Premier Mine. It was sampled extensively at one time, but insufficient diamonds were found to warrant profitable operations.

The slides were studied in some detail and the conclusion was reached that these were, in every major respect, identical to the thin sections of the Blue-black kimberlite of the Premier Mine. These two kimberlites are, therefore, correlated on the basis of this microscopic evidence.

## Carbonate-Rich Kimberlite

The Carbonate-rich kimberlite is a porphyritic, igneous rock, in which the phenocrysts originally consisted of olivine but are now altered to serpentine.

These serpentine pseudomorphs are set in a groundmass, in which we also find numerous replaced idiomorphic olivine grains, of smaller size, as well as flakes of chlorite and grains of perovskite.

### The Groundmass

The groundmass of the Carbonate-rich kimberlite differs from that of all the other kimberlites of the Premier Mine. Under low or medium magnification, the most prominent constituent of this groundmass is very dark, nearly opaque material, which surrounds most of the other minerals (Plate XI, Figure 2). In reflected light, it is nearly pure white and has a vitreous lustre.

When viewed under higher magnification and with a concentrated light source, some of the grains or portions of grains that form this material are clear and transparent, while the rest have a pale brown, cloudy appearance and are only translucent (Plate XIII, Figure 1). Both types are quite isotropic. It was not possible to separate any of this material from the rock. However, by using the oil immersion method on the edge of an uncovered thin section from which the Canada Balsam had been removed, it was found that its refractive index lies between 1.74 and 1.75. By using Pheigler's spot test with para-nitrobenzene-azo-resorcinol, it was found that the material gives a positive test for magnesium.

While the evidence is not conclusive, it is possible that this material is periclase.

This periclase (?) may be of secondary origin or it may have been the last mineral to crystallize out. In the groundmass, it replaces chlorite and crowds the serpentine pseudomorphs, giving them a somewhat ragged appearance.

From a search of the literature, it appears that periclase has never been reported as a primary mineral in igneous rocks. It is to be hoped, therefore, that some means may be found of separating these grains from the rock so that their true nature can be determined by chemical analyses or other means.

The most common occurrence of periclase is in metamorphic limestones (Rogers and Kerr, 1933), in which it has been reported from Italy, Sweden, United States, (Rogers, 1918), and Korea (Wanatabe, 1935).

That periclase may form from melts containing MgO, CaO, and $SiO_2$ is clear from experiments carried out at the Geophysical Laboratory in Washington (Osborne, 1943). From the data supplied by Osborne it is apparent that periclase forms when the $SiO_2$ in the CaO - MgO - $SiO_2$ mixture is below 40% and the MgO is above 12%. The temperature of formation of the periclase varies, between, at least 1,530 and 1,720 degrees Centigrade, and apparently depends on the ratio of the various components in the mixture. As the work on this ternary system was not done specifically for the determination of the stability field of MgO, much information is still required. A study of a multi-component system containing, besides MgO, CaO, and $SiO_2$, also $CO_2$ and $H_2O$ would probably provide the answers.

From the experiment mentioned above, it seems likely that periclase may form in a magma rich in magnesia and lime, and poor in silica. The Carbonate-rich kimberlite apparently formed from such a magma, as is evident from the chemical analyses of this rock (analysis No. 3, p. 91).

The effects of $CO_2$ and $H_2O$ on the crystallization cannot be evaluated at present, but Tomkeieff (1938) has already pointed out that the presence of $CO_2$ may even determine to some extent what minerals will be formed.

Other minerals present in the groundmass are perovskite, calcite, chlorite, and antigorite. The perovskite grains display the usual features, previously described. The calcite is in minute, irregular flakes, but whether or not these are secondary is not definitely known.

The antigorite occurs as flaky aggregates, which are commonly surrounded by the isotropic periclase (?), previously described. The chlorite flakes will be described separately.

## Olivine

While two generations of olivine were originally present in this rock, there is not the marked difference in size between the early and later formed grains that are found in the Micaceous kimberlite.

Both generations have been completely replaced by clear, colourless and optically positive serpentine. The results of investigation of this material by x-ray analysis were identical with those obtained for the serpentine from the Blue-black kimberlite.

Needles of rutile are common also in the replaced olivine grains of this rock. Magnetite is practically absent and the original olivine must have been poor in iron.

## Pyroxene

No pyroxenes were found in any of the thin sections cut from this rock. This mineral may have been altogether absent from this rock, or, less likely, it has been altered beyond recognition.

## Chlorite

Numerous flakes of chlorite occur in this kimberlite. They show typical anomalous interference colours. The mineral is optically negative, with a very small optic angle and is most likely penninite. It sometimes occurs in radiating aggregates. The individual flakes are much larger than the mica flakes observed in the Micaceous kimberlite. Many of them have been partially replaced by the isotropic periclase (?). This being the case, it is very likely that the rock at one stage contained an even larger percentage of chlorite than at present, and as the chlorite presumably represents mica, the rock may thus originally have been a micaceous kimberlite.

## Calcite

Besides the tiny flakes of calcite that occur in the groundmass, large rounded or irregular patches of calcite are also present. These are invariably surrounded by a wide zone of serpentine. This serpentine is not identical with that replacing the olivine as it appears to consist of flaky aggregates. The individual flakes have a more or less similar orientation. In places, it appears as if the calcite may be replacing this serpentine.

In hand specimen, these calcite grains look like fillings of vesicles, but there is no proof that this is actually the case.

Ilmenite

Ilmenite is not abundant in this rock. As in the other types of intrusive kimberlite, the grains have been marginally altered to perovskite, but here these perovskite borders are much wider. This may indicate that the original magma was rich in lime or that the solutions that brought about the subsequent alteration of the rock were rich in lime.

Magnetite

This mineral is present in very small quantity. It is almost never seen in thin sections of the rock.

Inclusions

A fair number of light coloured inclusions occur in the Carbonate-rich kimberlite. Most of these have a kernel, consisting of calcite. Their borders, especially in the case of the smaller ones, are often indefinite. This indicates assimilation by the magma. During this assimilation, secondary minerals have developed. These include clinopyroxene and isotropic grossularite, as well as periclase (?). As previously stated, the isotropic grossularite indicates a temperature of formation of at least 800 degrees Centigrade.

The secondary pyroxene, and occasionally the garnet, may appear interstitially between the constituent minerals of the kimberlite immediately around the inclusions.

The presence of calcite, diopside, and lime garnet indicates that these inclusions may originally have been fragments of limestone. The only known source of such material is the Dolomite series of the Transvaal system.

## The Mixed Zone of Carbonate-Rich and Micaceous Kimberlites

Field evidence has already been given to prove the existence of this zone. Microscopic examination of numerous thin sections of specimens taken from this zone, both on the 610-foot level and the 1,060-foot level, could not definitely substantiate the evidence already submitted. The sections were all practically identical with thin sections of the Carbonate-rich kimberlite, and the assimilation of the Micaceous kimberlite must have been nearly complete. While not visible in thin section, a number of hand specimens show clearly that the rock, in this mixed zone, is indeed a hybrid.

## Blue-Grey Kimberlite

Most of the thin sections of this rock clearly display its fragmental nature (see Plate XII, Figure 1). Irregular and rounded fragments of altered olivine, and occasionally of pyroxene, are found, together with the usual accessory minerals, perovskite and ilmenite. These are often accompanied by rounded, and sometimes irregular, fragments of pyroxenite, diabase (?), and shale (?), as well as kimberlite.

The individual fragments usually have an adhering film of a fine grained brownish substance, which, most likely, represents altered portions of the original groundmass of the rock from which this fragmental kimberlite was derived (Plate XII, Figure 2). Further proof of this is afforded by the inclusions of kimberlite, which has a groundmass of the same brownish material.

The minerals and rock fragments of the Blue-grey kimberlite are set in a matrix of clear, felted antigorite. This material was probably derived from the small fragments and mineral dust which originally constituted the groundmass of this fragmental rock.

Also present in the groundmass of this rock are clear, colourless needles of an unknown mineral. These crystals can be found radiating from the brown granular material surrounding some of the mineral fragments. The individual prismatic needles are, on the average, only 0.015 mm. long and 0.003 mm. wide. The extinction is oblique and varies between 20 and 30 degrees. The refractive index is higher than that of antigorite. No other optical properties could be determined and the mineral remains unidentified.

Olivine

No unaltered olivine was found in any of the thin sections examined. The original presence of the mineral must be assumed from the presence of the typical alteration products of olivine and of occasional idiomorphic crystals with the typical shape of olivine.

A number of the grains consist now of clear serpentine, which may be faintly green or yellow, and which for the most part is optically negative, though some is positive. Unfortunately, no clean separation of the two types could be made, and consequently it was not possible to get an x-ray analysis to compare with the optically positive serpentine found in the intrusive kimberlites.

This clear serpentine is in turn replaced by a fine felted mass of antigorite, with the disappearance of the usual "mesh" structure (Plate IX, Figure 2).

The antigorite finally makes way for talc, but talc may also replace the serpentine directly (Plate XIV, Figure 1).

During the change, of serpentine to antigorite and talc, the needles of rutile, which are usually present, are converted to sphene.

Tiny octahedra of magnetite are also associated with the serpentine. That this mineral has great stability is evident, since it persists through all stages of the alteration.

In a number of the serpentine grains, a strongly pleochroic alteration product is found. This is a green substance and is pleochroic from green to reddish-brown or pale yellow. In some of the flakes of this mineral the birefringence is abnormal, like that of some chlorites; in others it is normal, displaying up to second order (0.025) interference colours. The mineral is optically negative. This mineral was not positively identified, but in its optical characters it agrees closely with bowlingite, an alteration product of olivine.

Very tiny, rounded grains of zircon are sometimes present in the altered olivines. This observation was confirmed by the presence of zirconium lines in the spectrum of the powdered serpentine or antigorite.

## Pyroxene

While the original olivine has been completely altered, some comparatively fresh grains of pyroxene are present. These are never abundant and the original rock must have been relatively poor in this constituent, with a content probably less than 1%.

Hypersthene - This mineral is found in nearly all the thin sections. It invariably displays a wide reaction rim, similar to that found around the hypersthene of the Blue-black kimberlite. The grains may show partial alteration to serpentine and magnetite, and some of them also an incipient marginal change to diopside. The hypersthene shows the usual faint pleochroism and is optically negative (Plate XIV, Figure 2).

Diopside - A few anhedral grains of colourless diopside are present in the rock. These are usually quite fresh or may show a very slight marginal alteration to serpentine.

## Garnet

The original presence of this mineral is indicated by a small number of fragments, which are accompanied by the reaction rim previously described (see p. 57 ).

## Perovskite

Perovskite is a minor constituent of the rock, the grains occurring usually in the brown, granular portion of the matrix. Some are fresh looking, but most of them have been partially or completely converted to sphene.

## Ilmenite

Rounded grains and irregular fragments of ilmenite are present in the Blue-grey kimberlite. Where a grain retains its original boundary, the usual marginal change to perovskite can be seen, but this is absent at the margins of evidently broken grains. Thus, the indications are that the perovskite formed before the original rock was disrupted, and perhaps even during the magmatic stage.

Magnetite

The magnetite in this rock is apparently all secondary, as it always appears in close association with the alteration products of olivine or hypersthene. Using the method previously described, it was found that this rock contains approximately the same percentage of magnetite as the intrusive Blue-black kimberlite.

Inclusions

Numerous fragments of soft, altered shale are present in this rock. The shale has been converted largely to serpentinous material, probably by hydrothermal solutions. The source of these fragments is not definitely known, but it was most likely derived from the underlying shales of the Pretoria series.

Small fragments of limestone are also found. These have been recrystallized, but may have been in this condition when they were incorporated in the kimberlite. In view of the lack of metamorphism of this rock, it seems clear that the kimberlite magma, from which the fragmental Blue-grey kimberlite was derived, had crystallized completely before it reached the Dolomite series of the Transvaal system, which is apparently the only possible source of these fragments.

A number of rounded fragments of igneous rock inclusions also occur. These have been thoroughly altered and their texture is the only indication that they were originally igneous. Some have typical diabasic texture and have probably been derived from the diabase sills and dykes in the Transvaal system.

Of importance are the inclusions of intrusive kimberlite which are found in the Blue-grey kimberlite. These are all very similar in appearance and probably represent the intrusive rock from which the Blue-grey kimberlite was derived.

The groundmass of the inclusions is similar in appearance and probably in composition, to the brown granular borders of individual fragments and grains, previously described (see page 68). The only exception to this was found in one thin section, in which a fairly large fragment of kimberlite has a groundmass consisting of numerous small flakes of phlogopite, together with some antigorite and chloritic material.

The presence of mica, as the main groundmass mineral, is important. Providing this mica is primary, as it is believed to be, this means that the groundmass of the kimberlite was rich in mica, or consisted almost entirely of mica, and there is no need to postulate a groundmass which consisted partly of vitreous material.

The brown granular material in the groundmass is apparently an alteration product of the phlogopite. If this assumption is correct, and it seems reasonable, than the presence of this material in the outer zone of fragmental kimberlite indicates that mica was an important constituent of the rocks from which these agglomeratic tuffs were derived.

The primary minerals of the intact intrusive kimberlite inclusion, referred to above, were olivine (now completely altered to serpentine, antigorite, and talc) hypersthene, and ilmenite. Perovskite, partially altered to sphene, is also present, and may have been an original constituent.

Fragments of the "corona" of garnets also occur in some inclusions. This may indicate that the garnets were either derived from previously existing rocks or were crystallized out in depth and transported upward by the magma, and were fractured during the transportation. The latter assumption appears rather unlikely to be correct, as fragmentation can usually only take place in an already crystallized mass.

## Intermediate Kimberlite

The characteristics of this rock are much like those of the Blue-grey kimberlite, or portions of the Normal kimberlite, and a detailed description would only be a repetition of the points already mentioned.

The rock is fragmental in nature. As in the other two fragmental types of the outer zone, the fragments consist of individual minerals, foreign rock, and intrusive kimberlite.

The minerals present are also the same, and include altered olivine, hypersthene, and diopside, together with the accessories, perovskite and ilmenite.

Microscopic evidence further indicated that there is no reason to assume that the Intermediate kimberlite is a particular type of kimberlite, which can be separated from the other fragmental kimberlites on petrographic grounds. It may very well have formed from an intermingling of fragments of the Normal kimberlite with those of the Blue-grey kimberlite.

## Normal Kimberlite

The Normal kimberlite is a typical pyroclastic rock and this fact is well displayed in thin section. The rock is very similar, in nearly all respects, to the Blue-grey kimberlite. The major point of difference is in the alteration, which has gone farther than in the latter rock.

Normally, we find fragments of individual minerals, pieces of kimberlite, and foreign rocks, embedded in a matrix of secondary minerals.

### The Groundmass

The groundmass of this rock is apparently identical with that of the Blue-grey kimberlite, as we find both the clear areas of antigorite, and the brown granular borders, clinging to the mineral and rock fragments. The very small prismatic needles, found in the Blue-grey kimberlite, are again prominent in this rock. Calcite is also a fairly common constituent of the groundmass, at least in some parts of the rock.

Olivine

From the abundance of the alteration products of olivine, it must be assumed that olivine was the dominant mineral in this rock. Originally, two generations of this mineral must have been present, as we find two generations in some intrusive kimberlite inclusions. However, both generations have now been completely altered. The clear and colourless optically positive serpentine, found in some of the other kimberlites, is never found here. Instead, we find the grains replaced by very fine aggregates of antigorite, and this, in turn, is replaced in many places by talc. While the replacement by talc was the last stage in the alteration of the olivine of the Blue-black and Blue-grey kimberlites, in this rock the alteration may proceed even farther and carbonate may replace the earlier-formed alteration products. Stain tests proved the carbonate to be calcite. It usually appears in the centre of a grain and may be surrounded by a zonal arrangement of talc and antigorite (Plate XV, Figures 1 and 2).

The rutile needles so common in the serpentine pseudomorphs of the intrusive kimberlites are absent in this rock and, instead, we find a very small number of grains of sphene as inclusions in the antigorite and talc in a few sections. This would indicate that either titanium was practically absent from the original olivine or it was lost from this mineral during the subsequent alteration.

Pyroxene

Both hypersthene and diopside are present, in about the same amount, and having the same features, as in the Blue-grey kimberlite (for description see page 70).

Perovskite

This accessory mineral is present in small dark grains, showing the typical twinning. As in the Blue-grey kimberlite most of these grains have been partially converted to sphene.

Mica

Occasional flakes of phlogopite were noted in the thin sections of this kimberlite. This mineral is so scarce, however, that its presence may easily be overlooked.

Ilmenite

Ilmenite is present in fair amount and shows the usual alteration to perovskite around the edges of unbroken grains.

### Magnetite

All of this mineral is, as in the other kimberlites, secondary and is derived from the alteration of olivine and hypersthene. It is present in the same amount as in the Blue-black and Blue-grey kimberlites.

### Inclusions

Recrystallized, but otherwise unaltered, limestone fragments also occur in this rock. As has been pointed out previously, these were most likely derived from the Dolomite series of the Transvaal system.

The intact fragments of intrusive kimberlite are also of importance. At least one fragment was noted in which phlogopite flakes are an important constituent of the matrix. This again points to a micaceous matrix for the original kimberlite from which the Normal kimberlite was derived.

## The Inner Zone of Fragmental Kimberlites

### The Western Fragmental Kimberlite

This is a very heterogeneous rock and more thin sections than are at present available would be required to make a complete study.

The heterogenity of the rock is well displayed by the contrast in appearance of specimens collected at different points on the 610- and 1,060-foot levels.

The exposed portions of this rock on the 1,060-foot level are fairly similar in appearance. The reason for this is that, in this part of the mine at least, it consists entirely of small rock and mineral fragments embedded in a matrix of secondary material, mainly antigorite.

As is the case in the kimberlites of the outer fragmental zone, individual mineral grains and fragments are wholly, or in part, surrounded by a brownish granular material that could not be identified. Under high magnification, very small flakes of partially altered phlogopite mica can occasionally be seen surrounded by this material. The association again suggests that the granular material may have formed during the alteration of the mica. This alteration product is most likely all that is left of the original groundmass of the kimberlite from which this fragmental rock was derived.

Olivine

This mineral has now been completely altered to serpentine, antigorite, and talc. The fact that most of the grains consist of a mixture of these products was not known originally and an attempt was made to analyse the powdered material by x-rays. The results were, as could be expected, of no value whatever.

The presence of some very large (25 mm.) grains of altered olivine is notable. These probably had a comparatively deep-seated origin.

Rutile needles are present in the serpentine grains of some thin sections, but may be altogether absent. Aggregates of brown sphene also occur, but their distribution is erratic. As in the other kimberlites, this mineral probably formed from the rutile.

Magnetite is apparently absent as an alteration product of the olivine, indicating this was an iron-poor variety.

## Pyroxene

Both diopside and hypersthene are again present in this rock, although in small amount. As in the other kimberlites, the diopside is usually quite unaltered, whereas the hypersthene usually shows partial conversion to serpentine.

## Perovskite

This mineral is present, but has an uneven distribution and has largely been changed to brown sphene.

## Ilmenite

Ilmenite is not very conspicuous in this rock. The grains that are present have been partially altered to perovskite and sphene.

## Magnetite

Magnetite is practically absent from this rock.

The Western fragmental kimberlite of the 610-foot level is different in appearance from that of the 1,060-foot level, and apparently there is a vertical change in the material constituting this column of rock.

Thin sections cut from the 610-foot level specimens show an abundance of mineral and rock fragments set in a matrix which is predominantly of the brown granular material previously described. The predominance here of this material is one of the major differences between the Western fragmental kimberlites on the 610- and 1,060-foot levels.

No attempt is made to correlate this kimberlite with any of the other kimberlites in the mine. From the field evidence, it is clear that this type came into existence after the outer zone of fragmental kimberlites and the Blue-black kimberlite were already in place. It is clear, then, that this type may include material from all these kimberlites or from their deep-seated equivalents.

## The Eastern Fragmental Kimberlite

Most of this rock is fairly homogeneous and it consists of small rock and mineral fragments, set in a matrix of secondary minerals.

While the rock is homogeneous in appearance, it is actually made up of fragments of a variety of different kimberlites, and as many as three varieties were found in one thin section. Some of these fragments are very similar to the Blue-black kimberlite in appearance.

Of interest, too, are the fragments of kimberlite with a micaceous groundmass. These are practically identical to similar inclusions found in the outer zone of fragmental kimberlites. As in the latter case, the alteration of phlogopite gives rise to brown granular or flaky material. Individual mineral grains may have a border of similar material, in which small remnants of phlogopite can occasionally be seen.

Olivine

The olivine in this rock has been completely replaced by optically negative serpentine, antigorite, and talc. Rutile needles are absent in the alteration products and, instead of this mineral, we find grains and aggregates of sphene. Magnetite is apparently altogether absent and the original olivine must have been poor in the fayalite molecule.

Pyroxene

Fragments of hypersthene and diopside are present. As usual, the hypersthene shows a fairly wide reaction rim and partial alteration to serpentine.

## Mica

Small flakes of faintly pleochroic phlogopite are common only in the groundmass of some of the kimberlite inclusions, but they occur also in the borders of secondary material around some mineral fragments.

## Perovskite

Perovskite was found only in one of the kimberlite inclusions, where it occurs in the groundmass.

## Ilmenite

Some very large grains of ilmenite, up to 20 mm. in diameter, occur in this rock. These show the usual marginal alteration to perovskite. Spectroscopic and chemical analyses indicate that this mineral contains an appreciable amount of chromium, and magnesium, as it does in the Micaceous kimberlite.

## Inclusions

Apart from the intrusive kimberlite inclusions, already mentioned, we find, specially on the 610-foot level and in the open pit, the large rounded inclusions of peridotitic rocks, mentioned in chapter III.

Thin sections of a number of these were studied.

These rocks are all coarse grained and probably of deep-seated origin, as pointed out by Wagner (1928) and others.

Many of these inclusions, specially the smaller ones, have been completely serpentinized. The larger ones usually display a relatively fresh kernel, surrounded by a zone of complete alteration to serpentine.

The following minerals occur together:

Olivine, bronzite.

Olivine, bronzite, biotite.

Olivine, bronzite, pyrope.

With the evidence at hand, it is possible only to say that the Eastern fragmental kimberlite was formed from a variety of kimberlites, none of which can, with certainty, be correlated with any of the kimberlites, now exposed in the mine.

## Summary of the Microscopic Work

1) The Normal, Blue-grey, Western fragmental, and Eastern fragmental kimberlites are rocks which can best be described as agglomeratic tuffs.

2) The Blue-black, Micaceous, and Carbonate-rich kimberlites all lack the fragmental nature of the above types and are intrusive kimberlites.

3) Mineralogically the Normal, Blue-grey, Western fragmental, Eastern fragmental, and Blue-black kimberlites are very similar and they contain mainly altered olivine and minor amounts of pyroxene. The Western and Eastern fragmental kimberlites differ from the rest of this group in that they contain very little or no secondary magnetite.

4) With the exception of the Blue-black kimberlite, which is a doubtful case, it seems likely that all the kimberlites originally had a micaceous groundmass.

5) The Micaceous and Carbonate-rich kimberlites contain very few or no primary pyroxenes and differ in this respect from the other kimberlites.

6) While small limestone fragments in the Normal and Blue-grey kimberlites have not been appreciably altered, similar inclusions in the Micaceous, Blue-black, and Carbonate-rich kimberlites have been thoroughly metamorphosed with the development of pyroxene, garnet, serpentine, and other minerals.

7) The Micaceous and Carbonate-rich kimberlites also differ from the Normal, Blue-grey, and Blue-black kimberlites in that they contain little or no secondary magnetite derived from the alteration of olivine.

8) The Carbonate-rich kimberlite differs from the other kimberlites in having a groundmass in which calcite and a mineral, tentatively identified as periclase, are present.

9) Alteration is most pronounced in the Normal kimberlite and is least noticeable in parts of the Micaceous kimberlite.

# CHAPTER V

# THE GENESIS, MAGMATIC HISTORY AND ALTERATION OF THE KIMBERLITE

## The Genesis of the Kimberlite

It must be stated at the outset that no new ideas concerning the genesis of kimberlite will be given here. Many competent petrologists have studied this problem and the final solution has not yet been found.

Voit was of the opinion that kimberlite may have been derived from the differention of a magma of diabasic character and expressed his view as follows: "I am inclined to look upon the kimberlite as the final evidence of volcanic activity (in the largest sense of the word) which took place immediately after the Karroo period, beginning with the extrusion of very siliceous rocks of diabasic character, which we find in the lower beds of the Karroo formation. During the later eruptions these diabasic rocks take more and more a normal character till ultimately, in the extrusion of the kimberlite, they pass into an ultrabasic rock chiefly containing pyroxene as a constituent mineral" (Voit, 1907).

It is not clear how Voit arrived at the conclusion that pyroxene is the main constituent of kimberlite. Most other investigators agree that olivine is the most essential mineral.

Wagner states it is possible "that the kimberlite magma was generated by the liquefaction, consequent upon relief of pressure, of potentially fluid portions of a universal zone or couche of holocrystalline peridotite (the Sima zone of Suess)" (Wagner, 1914, p. 117).

Du Toit arrived at the conclusion that "kimberlite has been produced by the shattering of various holocrystalline basic and ultrabasic rocks and the incorporation of this material by a magma of ultrabasic character" (Du Toit, 1906).

Du Toit's hypothesis is substantiated by work done by Holmes, who found that the "magma of ultrabasic character" of du Toit can perhaps be regarded as the chemical equivalent of olivine-melilite, to which abundant $H_2O$ and $CO_2$, as well as CaO, $P_2O_5$, and other minor constituents have been added.

Holmes states that this hypothesis does not merely imply that the groundmass of kimberlite is simply hydrothermally altered olivine-melilite. He goes on to say that good evidence is present in the Kimberley (Cape Province) pipes that this is not so. Olivine-melilite is one of the most potent agents of metamorphism and transfusion, and yet the temperature of the mobile part of the kimberlite (of the Kimberley pipes) was so low that fossil wood, coal, and shale inclusions remained unaltered (Holmes, 1936).

This is certainly so, but since it was found at the Premier Mine that only the fragmental kimberlites contain inclusions which are not metamorphosed, it seems possible that the "mobile part" of which Holmes writes may refer only to the fragmental kimberlites.

There is not much doubt that the actual intrusive kimberlites are capable of causing strong metamorphism. This was found to be the case with the intrusive kimberlites of the Premier Mine, which have thoroughly metamorphosed inclusions of limestone. Du Toit also found evidence of metamorphism at Theron's Mine, Paarde Berg East, and Kamfersdam in the Cape Province (Du Toit, 1906).

Taljaard studied this problem from another angle and based his conclusions, to a certain extent, on field evidence. This author is of the opinion that kimberlite may be the hydrothermally altered parent rock of melilite basalt (Taljaard, 1936).

The ideas of van Biljon concerning the genesis of kimberlite were mentioned in chapter III. It is of interest to refer again to the suggestions of this author. He raised the question whether kimberlite may not have been derived from the transformation of certain shales of the Pretoria series (van Biljon, 1948).

While this speculation may be interesting in itself, it cannot be taken very seriously. Apart from the difficulty involved in explaining the chemistry of such a change, there remain also certain other features which cannot be summarily dismissed.

The shales, from which the kimberlite were supposed to have been derived, occur above the Dolomite series. However, fragments of limestone, presumably derived from this series, occur in the kimberlite of the Premier Mine. This factor alone would appear to testify against the suggestion of van Biljon. Furthermore the inclusions of peridotitic rocks, all apparently of deep-seated origin, cannot be accounted for by assuming a comparatively shallow point of origin for kimberlite. The strongest argument against such a theory, however, is certainly the occurrence of kimberlite pipes in areas where shales are altogether absent. The way in which van Biljon made use of chemical analyses to arrive at this conclusion must be strongly censured.

Of all these hypotheses, that of Holmes is apparently the most acceptable. It does not completely solve the problem, however, for, as Holmes himself points out, there is reason to believe that olivine-melilite itself may be a syntectic product.

## The Magmatic History of the Premier Kimberlites

For an adequate study of this problem, a large number of good chemical analyses would be required. These, unfortunately, are not available.

Most chemical analyses of kimberlite must be used with a certain amount of caution. These rocks are usually very thoroughly altered and may also contain numerous inclusions of sedimentary and other rocks. Allowance could be made for these inclusions, of course, if their compositions and the amount present were known.

Since these rocks are usually completely altered, the chemical analyses, as given, will not be a true reflection of the original composition of the rock. To arrive at this original composition, it would be necessary to know, at least, which minerals were originally present and which materials were involved in the alteration. This would be an impossible task, or at best a very difficult one, and it is small wonder that no such attempts have ever been published.

No attempt at such recalculations can be made as a result of the present study since the groundmass of the kimberlites, especially, is at present an unsurmountable obstacle. For the purpose of this discussion, the chemical analyses given by Williams (1932) and Daly (1925) will be used without modification. It must be stressed, however, that the conclusions reached can only be regarded as tentative since too many points concerning the analyses are in doubt.

Most of the analysed rocks apparently come from, or just above, the 610-foot level. At this level the amount of alteration of the various kimberlites are roughly the same, and consequently the amount of error introduced by this factor will be about the same for all the analyses.

## ANALYSES OF KIMBERLITE

Nos. 1-4: Williams, 1932, p. 146. No. 5: Daly, 1925, p. 672.

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| $SiO_2$ | 46.71 | 38.48 | 30.80 | 19.64 | 7.01 |
| $Al_2O_3$ | 3.85 | 2.03 | 4.60 | 1.27 | 0.99 |
| $Fe_2O_3$ | 5.23 | 10.09 | 6.32 | 9.00 | 8.06 |
| FeO | 3.94 | 0.28 | 0.80 | 2.70 | 3.84 |
| $TiO_2$ | 1.60 | 2.20 | 1.30 | 1.72 | 1.53 |
| $Cr_2O_3$ | 0.13 | 0.14 | 0.15 | -- | Nd. |
| NiO | 0.22 | 0.11 | -- | -- | Nd. |
| MnO | 0.16 | 0.16 | 0.04 | 0.47 | 0.68 |
| CaO | 5.04 | 12.72 | 18.20 | 20.16 | 24.76 |
| MgO | 22.45 | 25.92 | 24.55 | 22.17 | 24.82 |
| $K_2O$ | 3.67 | 0.44 | 0.82 | Nd. | 0.43 |
| $Na_2O$ | 1.51 | tr. | tr. | Nd. | 0.39 |
| $CO_2$ | 0.29 | 0.68 | 6.27 | 15.84 | 16.93 |
| $P_2O_5$ | 0.11 | 0.07 | 0.11 | 1.14 | 1.22 |
| $H_2O$ - | 1.84 | 0.35 | 0.60 | Nil | 0.16 |
| $H_2O$ + | 3.34 | 6.84 | 6.33 | 4.64 | 9.61 |
| S | tr. | 0.05 | 0.27 | -- | -- |
| Ignition loss | | | | 1.32 | |
| Totals. | 100.09 | 100.57 | 101.16 | 100.07 | 100.43 |

1. Fragmental kimberlite. Average of five analyses.
2. Intrusive kimberlite, probably the Blue-black kimberlite.
3. Intrusive kimberlite, probably the Carbonate-rich kimberlite.
4. Partly replaced kimberlite dyke.
5. Completely replaced kimberlite dyke.

Apart from the variation of the alkalies, the most outstanding feature of the analyses is the steady increase in lime from the fragmental rocks to the dyke rocks, and the accompanying sharp decrease in $SiO_2$. This is well shown in the variation diagram (Figure 2, page 93).

This increase in CaO may be due to one of two factors or to a combination of both.

a) It may be due to the partial or complete absorption of limestone fragments derived from the Dolomite series.

b) It may be due to a normal trend in the magmatic differentiation of ultrabasic rocks.

There is some evidence of the former having taken place in the Blue-black, Micaceous, and Carbonate-rich kimberlites.

While no positive evidence for the second hypothesis could be found at the Premier Mine, the indications are that this process is indeed a normal one. Carbonates, often of late crystallization, are associated with ultrabasic rocks at Alnö (von Eckermann, 1948), Eastern Uganda (Davies, 1947), Southern Rhodesia (Mennell, 1946), The Fen area of Norway (Brögger, 1921), and at Spitskop in the Eastern Transvaal (Strauss and Truter, 1950).

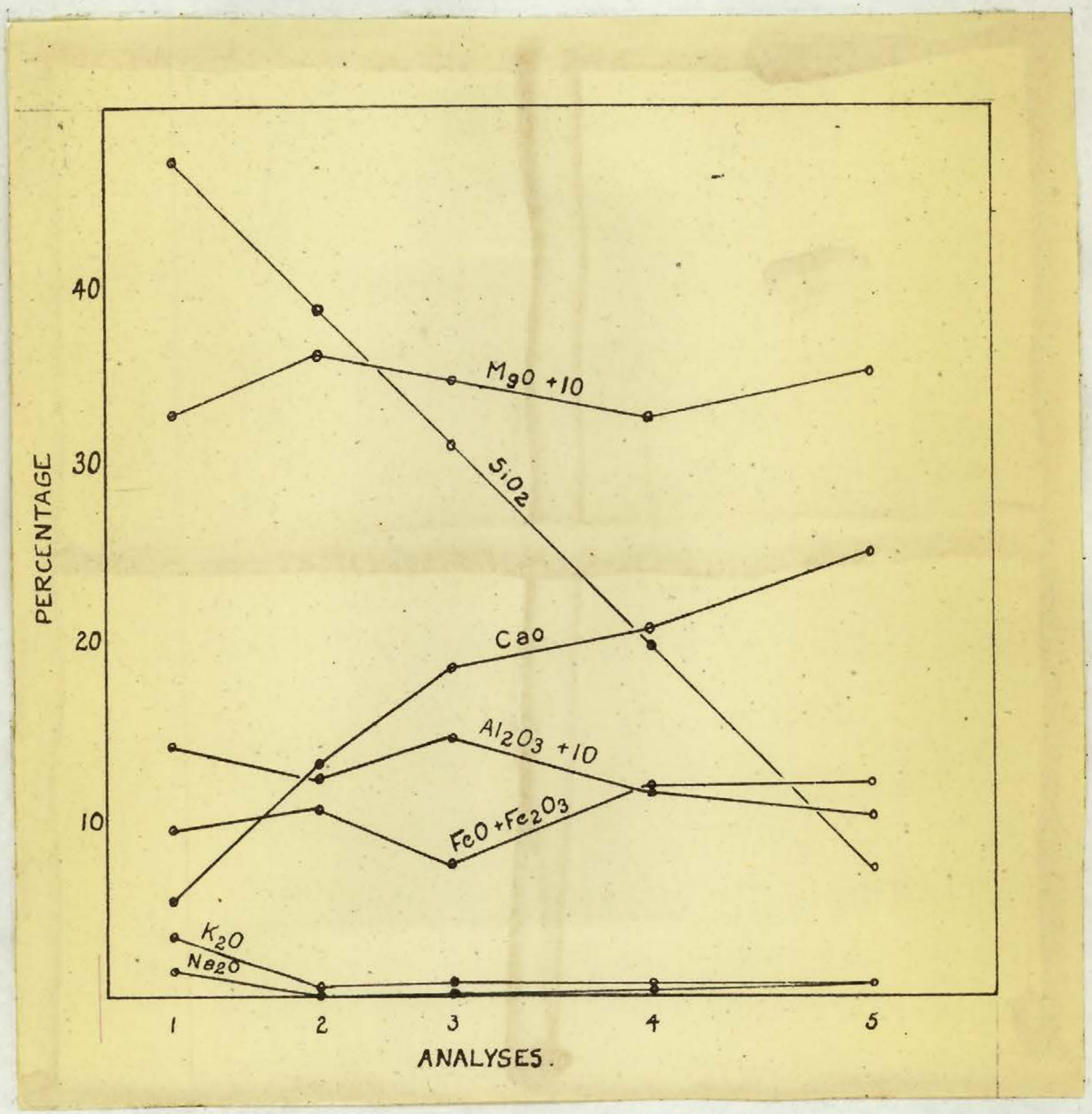



Figure 2. Variation Diagram of the Kimberlites.

Percentage of other Oxides plotted against Silica percentage.

## The Alteration of the Kimberlite

It would be a difficult task to study the alteration of most of the kimberlites in any but a qualitative way. If both unaltered and altered kimberlites were available, chemical analyses of types grading from one to the other would be of value in studying the changes which took place.

In the Premier Mine, only the Micaceous kimberlite occurs in comparatively fresh and in altered phases. The alteration in this rock does not reach exactly the same stage as the alteration of, for instance, the Normal kimberlite and, in any case, no chemical analyses are available.

The main constituents of the Premier kimberlites are, or rather were, olivine, pyroxene, and mica.

Of the alteration of the mica, very little is actually known. In some cases chlorite (penninite) may appear but usually the alteration products are of such an indefinite nature that normal petrographic methods are inadequate to solve this problem.

Of the pyroxenes, diopside was apparently quite stable under the conditions which prevailed, while hypersthene alters in about the same way as the olivine.

The titanium minerals in the kimberlite make up only a small percentage of the rock. These minerals, however, also undergo some marked changes and their alteration will consequently be discussed.

1) <u>The Alteration of the Olivine</u>

In the alteration of the olivine, a number of steps were noted. None of the kimberlites showed all the stages and the information had to be obtained by a systematic study of several types of the rock. In brief, these steps were as follows:

Olivine ⟶ Serpentine ⟶ Antigorite ⟶ Talc ⟶ Carbonate

The change of olivine to serpentine is accepted, by most petrologists, to take place without a change in volume. If these volume relations are to hold, the usual equations written for this reaction are no longer valid and the equation given by Turner (1948) must be used:

$$\underset{\text{Forsterite}}{2.29\ Mg_2SiO_4} + 1.82\ H_2O \rightarrow \underset{\text{Serpentine}}{0.91\ H_4Mg_3Si_2O_9} + \underbrace{1.85\ MgO + 0.48\ SiO_2}_{\text{Removed in solution}}$$

Turner, however, points out that even this equation is not a satisfactory one as large quantities of MgO are removed and consequently magnesia metasomatism of the adjacent rocks could be expected where serpentinization is taking place. At the Premier Mine, as well as most other places, such magnesia metasomatism is lacking in the adjacent rocks.

If serpentine and antigorite are considered to be dimorphs of the compound $H_4Mg_3Si_2O_9$ (Selfridge, 1936), then the change of serpentine to antigorite is merely a structural one, i.e. antigorite was the more stable modification under the prevailing conditions.

Assuming no removal of magnesia, the change of serpentine or antigorite to talc requires the addition of silica and, of course, the loss of some water. Solutions containing silica could be provided by later acid intrusions. These, however, are absent at the Premier Mine. Due to the ultrabasic nature of the kimberlite magma, it is very doubtful that this additional silica could be derived from the same source as the magma.

According to Turner, the removal of silica and also of considerable magnesia is required during the alteration of olivine to serpentine. It seems logical to assume that this silica would be available to transform serpentine and antigorite to talc in other parts of the same rock-mass. Assuming, once more, an isovolumetric change, the following reaction shows the nature of this change:

$$\underset{\text{Serpentine}}{H_4Mg_3Si_2O_9} + 1.16\ SiO_2 \rightarrow \underset{\text{Talc}}{0.79\ H_2Mg_3Si_4O_{12}} + \underbrace{0.63\ MgO + 1.21\ H_2O}_{\text{Removed in solution}}$$

Where the magnesia set free by this reaction or in the alteration of olivine to serpentine migrates to is not known. The exposed "wall" rocks of the Premier Mine do not show the influence of magnesia metasomatism. The question may arise whether this magnesia is not, in part at least, represented by the colloidal magnesium-hydroxide which is found, together with magnetite and calcite, replacing late kimberlite dykes (Chapte VI). On the other hand, it is also possible that this equation does not indicate the true nature of the change.

The final change is to a carbonate. Strictly speaking, however, this is actually a replacement and not an alteration. Stain tests proved this material to be calcite. The absence of dolomite or magnesite is perhaps a little curious in view of the presence of so much magnesium in the rock.

The origin of the calcium carbonate is most likely to be sought in hydrothermal solutions. Evidence for the existence of such solutions is found in the abundance of calcite present as a replacement product in the replaced kimberlite dykes.

The following table shows the stage of alteration reached by the various kimberlites.

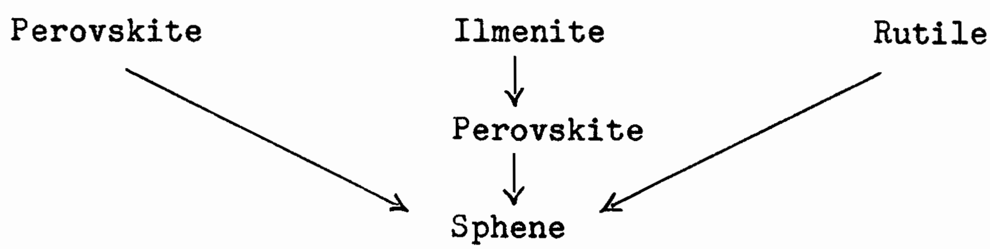
| Kimberlite | Olivine | |
|---|---|---|
| | Unaltered | Alteration and replacement |
| Normal | None | Antigorite, talc, calcite |
| Blue-grey | None | Serpentine, antigorite, talc, calcite |
| Blue-black | None | Serpentine, antigorite, talc |
| Western fragmental | None | Serpentine, antigorite, talc |
| Eastern fragmental | None | Serpentine, antigorite, talc |
| Micaceous | Present | Serpentine |
| Carbonate-rich | None | Serpentine |

The fragmental kimberlites, and portions of the Blue-black kimberlite, show the most advanced stages of alteration and replacement. While an insufficient number of thin sections, from critically located points, are available, the indications are that the alteration and replacement of the olivine reached a maximum in the fragmental kimberlites, as well as in the portions of the intrusive Blue-black kimberlite which were situated closest to the fragmental kimberlites.

This would seem to be the logical result of solutions passing through the fragmental material, which would naturally offer the least resistance to the passage of such solutions.

2) <u>The Alteration of the Titanium Minerals</u>

The titanium minerals show the following changes:




Perovskite and ilmenite are the primary titanium minerals. Rutile is secondary and is found in the serpentine derived from olivine.

The borders of perovskite found around most ilmenite grains have been previously described. This perovskite is clearly of secondary nature. The change from ilmenite to perovskite requires the removal of Fe and the addition of Ca. This can be brought about by the substitution of CaO for FeO in the $FeTiO_3$ molecule.

Wagner (1914) has already pointed out that part of this substitution may have taken place during the magmatic phase of the kimberlite. This presupposes the presence of CaO in the kimberlite magma.

Observations on thin sections have shown that sphene apparently occurs only in those kimberlites in which we find talc as an alteration product. It seems possible that this restricted occurrence has some genetic significance.

It has already been shown that solutions containing $SiO_2$ are necessary for the formation of the talc. Some of this silica must also have been available to form sphene from rutile.

$$\underset{\text{Rutile}}{TiO_2} + CaO + SiO_2 \longrightarrow \underset{\text{Sphene}}{CaTiSiO_5}$$

The fact that the rutile will change at all is a little strange, as this mineral is usually stable under ordinary conditions of weathering. Apparently, it was unstable under the conditions of hydrothermal alteration of the kimberlites.

3) <u>The Time of the Alteration</u>

Since Benson's discussion of the serpentinization problem (Benson, 1918), most authors agree that this process is an autometasomatic one. While the alteration of the kimberlites, therefore, may, like that of the peridotites, have been mainly an autometasomatic process, it is also quite certain that some of the alteration took place after the main magmatic stage had passed.

Evidence for this lies in the alteration of many of the inclusions of foreign rock in the kimberlite. The Normal and Blue-grey fragmental kimberlites contain inclusions of shale, which must have been incorporated in the rock during its fragmentation, as these fragments do not show any sign of assimilation or of contact metamorphism.

These fragments have been thoroughly serpentinized and the conclusion must be that this serpentinization followed the fragmentation of the rock.

# CHAPTER VI

## REPLACED KIMBERLITE DYKES

Very conspicuous dykes occur in various parts of the mine. These consist of black or bluish-black, distinctly magnetic rock, in which tiny grains of calcite are well displayed. In a few of these dykes, especially on the 610- and 660-foot levels, green pseudomorphs of serpentine, after olivine, can be seen in the dense, dark matrix. Where present, the larger serpentine grains are elongated parallel to the walls of the dykes (Plate IV, Figure 2).

These dykes have their major development in the northwestern part of the mine, where they are found branching in all directions. They generally taper out toward the contact with the country rock; some only a few inches wide persist for long distances but have not been observed intersecting the country rock.

The dykes are usually flanked by rocks of the "mixed" zone of Micaceous and Carbonate-rich kimberlites, previously described. Sharp contacts with this zone, as well as with the other kimberlites, were observed.

### Previous Work

Wagner described these dykes, but made no particular study of the rocks (Wagner, 1914, p. 99). He suggested that they may represent replaced kimberlite dykes.

Williams (1932) is of the same opinion as Wagner and he gives a recalculated chemical analysis of the dyke rocks, with which he attempts to prove his point by comparing it with chemical analyses of kimberlite.

Daly was opposed to this theory and, after a detailed study of these rocks, came to the conclusion that they were originally dykes consisting of primary calcite, magnesium hydroxide, magnetite, and perhaps periclase, together with some serpentine (Daly, 1925).

## The Present Investigation

During the present work, it was considered advisable to re-study these dykes as a larger number, and probably better, exposures were available than in the past.

When inspecting a suite of thin sections of the dyke rocks under the microscope, it is found that a number of them have the usual minerals and features of kimberlite, while others now consist of carbonate, magnetite, and amorphous or colloidal material, as well as some serpentine and other minor constituents. These varieties occur in connected dykes and such heterogenity can only be due to irregular replacement. From this evidence alone it therefore seems clear that we have here to do with replaced dykes.

### The Original Dyke Material

Before the actual replacement can be studied, it is necessary to find out what the nature of these dykes was before replacement took place. Thin sections of the dyke which terminates close to the hoist chamber on the 610-foot level give the best information.

The porphyritic structure of this rock is very similar to that of the Carbonate-rich intrusive kimberlite (Plate XVI, Figure 1). Idiomorphic olivine crystals, now completely replaced by serpentine, carbonate, and sometimes magnetite, occur. These are set in a fine grained matrix, which is already partly replaced. Together with the replacing material, we find remnants of chlorite flakes. These are smaller in size but otherwise similar to the chlorite found in the Carbonate-rich kimberlite, and possibly represent altered mica.

Small grains of perovskite occur in about the same amount (1.6%) as in the Carbonate-rich kimberlite. This mineral is also found in fringes around the rather small grains of ilmenite present in the rock.

The isotropic material which was found in the groundmass of the Carbonate-rich kimberlite, and which tentatively was identified as periclase, is also present in the partially replaced dyke rocks, although in smaller amount.

Judging by the general appearance of the partially replaced dyke rock in thin section, and by the minerals present, it seems likely that the dykes were originally kimberlite which did not differ very much from the Carbonate-rich kimberlite.

The Replaced Rock

While some dykes or portions of dykes display the features just described, the majority of them are as unlike kimberlite as is possible. Sections taken from dykes of this type show a large number of irregular patches, and sometimes veinlets, of carbonate, usually surrounded by a narrow border of clear isotropic material. Magnetite is abundantly present in large grains and very small particles and is usually embedded in isotropic material, similar to that which surrounds the carbonate grains (Plate XVI, Figure 2). A large number of the magnetite grains show a curious arrangement. A central solid grain of magnetite, with a square or irregular outline, may be present. Around this centre and embedded in the clear isotropic material may be found tiny particles of magnetite in a number of concentric zones. Some of these particles may be aligned in such a fashion that they appear to be under the influence of the magnetic field of the central magnetite grain (Plate XVII, Figure 2).

Some serpentine, usually in small irregular patches, is distributed through the rock. Large grains of the same mineral do occur but are scarce.

A small number of perovskite grains also are present but this mineral has mostly been altered to sphene.

The carbonate of this rock was submitted to staining with copper mitrate and ammonium hydroxide. All the grains took on a blue stain, thus proving that the mineral is calcite (Rogers, 1940).

A number of thin sections were partially covered and the uncovered portions treated with malachite green. This analine dye has the property of staining amorphous or colloidal material (Holmes, 1921, p. 276). It was found that the clear, nearly colourless, isotropic material took on a deep green stain, while the other material, with the exception of some of the serpentine, was not affected. This isotropic material is thus amorphous or in a colloidal state. Larsen, using a different technique, found the same and furthermore came to the conclusion that the material is magnesium hydroxide in a colloidal or metacolloidal state (Daly, 1925).

## The Replacement

The complete sequence of the replacement in this rock can unfortunately not be studied due to the absence of the unreplaced original kimberlite.

The study of the partially replaced rocks is of some value but even here the replacing material - calcite, magnetite, and colloidal magnesium hydroxide - is already present in appreciable quantity. The calcite forms irregular patches in the groundmass. This mineral often shows a radiating structure and may also show uneven extinction (Plate XVIII, Figure 1). It seems quite clear that the calcite is here present as a replacement of some other mineral.

In a limited number of places, the calcite is closely associated with a clear, colourless material with a low birefringence, which appears to be a fibrous serpentine. The calcite seems to be replacing this material.

Similar fibrous serpentine (?) was found in the Carbonate-rich kimberlite and in this rock, too, calcite seems to be replacing this mineral in a number of places. While this gives an indication of the mineral which is replaced by the calcite, it is still not known what this serpentine (?) is replacing.

In the completely replaced rock, the calcite grains are even more numerous. The individual grains are irregular and sometimes form comparatively large aggregates, which apparently represent completely replaced serpentine grains. The calcite sometimes surrounds or encloses grains of magnetite, which may themselves be surrounded by the colloidal material. This mode of occurrence seems to indicate that the deposition of calcite went on longer than that of the other material.

The magnetite grains of the partly replaced dyke rock are usually small and irregular. For the most part they occur disseminated through the groundmass, where they are always found in the colloidal magnesium hydroxide. Some of these grains may be an original constituent of the kimberlite. In the more advanced stages of replacement this mineral is found to replace the serpentine pseudomorphs of olivine. In some of the smaller grains this replacement may be complete and magnetite pseudomorphs of olivine are present in a few places (Plate XVII, Figure 1).

In the completely replaced rock, the magnetite grains are of a much larger size than in the partially replaced rock, and a larger number of them are idiomorphic. It is clear that, even if some of the magnetite is original, a substantial addition of material to form this mineral has taken place. The arrangement of small magnetite particles around a central grain, already described, may very well be an indication of this.

In both the partially and completely replaced dykes, the colloidal magnesium hydroxide is present as an interstitial filling. While clear areas of this material are found in the incompletely replaced dykes, especially surrounding the calcite grains, they practically always include magnetite particles in the completely replaced dykes.

Associated with the magnesium hydroxide are granules and aggregates of a faintly yellow isotropic material, similar to that which had been tentatively identified as periclase in the Carbonate-rich kimberlite. Periclase could be expected to be associated with the $Mg(OH)_2$, as dehydration of this material would give rise to periclase.

While the presence of colloidal magnesium hydroxide and calcium carbonate can be explained by postulating hydrothermal solutions, the presence of so much magnetite poses a problem.

The temperature of the incoming solutions was probably below 750 degrees Centigrade, as Smyth (Daly, 1925) found that periclase formed from the colloidal magnesium hydroxide at that temperature. Periclase, if this mineral is actually periclase, is only a minor constituent of the dykes.

The melting point of magnetite lies above 750 degrees Centigrade, and it is thus certain that the magnetite could not have been in a molten state.

Colloidal $Fe_3O_4$ is not known to exist and it seems more reasonable to argue that $Fe_2O_3$ was originally present in colloidal solution and that this was later oxidized to form magnetite.

Smyth (Daly, 1925) thought that the magnetite may have been in mechanical mixture with the rest of the replacing material. No evidence for this could be found during the present study.

Daly (1925) argued that the magnetite may have been derived from the kimberlite itself. It has already been pointed out that this mineral is present only in the older kimberlites of the Premier Mine and there only as one of the products of the alteration of the ferromagnesian minerals. The Carbonate-rich kimberlite, which most resembles the original dyke rock, contains practically no magnetite at all. It therefore seems unlikely that the magnetite could have been derived from any of the kimberlites now exposed.

While the origin of these hydrothermal solutions is still unknown, it seems likely that they represent the final phase of the magmatic activity which gave rise to the various kimberlites.

No new analyses of these replaced dykes are available and an insufficient number of satisfactory analyses are in existence. Consequently, no precise quantitative study of the metasomatic replacement can be made.

It is assumed by most petrologists that an isovolumetric relationship exists between incoming and outgoing material during metasomatism. This being the case it becomes necessary to take the volumes of material into consideration when comparing unreplaced and replaced rocks. Barth (1948) proposed a system of recalculating rock analyses to equal volumes. This system is based on the assumption that the oxygen content of a rock remains constant during metasomatism. In Barth's method, the usual chemical analyses are recast to give the number of cations associated with 160 oxygen ions contained in the "standard cell" of a rock. In doing so, the volumetric requirements are automatically taken care of.

It was found, however, that when this system of Barth's was applied to chemical analyses of these dyke rocks, one major difficulty arose. According to Barth, the number of outgoing and incoming cations should be the same. When the calculations were made, however, a discrepancy always appeared. Considering the nature of the rocks, this is not very strange. During the replacement, colloidal solutions were present and it is doubtful whether the oxygen in the rock remained constant at all under such conditions.

This matter was taken up with Professor Barth and, in a written communication to the author, he stated that a theory of calculation valid for many silicate rocks may not be directly applicable to these dyke rocks since they are rich in $CO_2$ and $H_2O$. "The underlying reason for this shortcoming may be complicated. I may offer the suggestion that the reaction mechanism silicate $\rightarrow$ silicate often is different from that of silicate $\rightarrow$ carbonate. The transformation of a silicate rock into another silicate rock (for instance, gabbro into amphibolite) may be regarded as a true metasomatic reaction (i.e. an exchange atom for atom). The transformation of silicate into carbonate would seem to be effected, in most cases, not by simultaneous exchange, but by simple solution and reprecipitation. The reason for this again would seem to be that carbonatization usually takes place in the upper parts of the crust where rocks are more loosely integrated and permeable for hydrous solutions - in short, where the problem of place is unimportant, and, consequently the transformations do not follow the 'volume law' of Lindgren".

While the action of hydrothermal solutions was postulated here as one way in which these dykes could have obtained their curious composition, it is also possible that another explanation may be valid. From general considerations, it seems likely that it may be difficult or impossible to distinguish between replacement which took place late during the magmatic phase, and later hydrothermal replacement. This can be illustrated by an example.

In the Fen area of Norway, carbonates are present in many of the rocks. While Brögger (1921) was of the opinion that these carbonates are an original constituent, Bowen (1924) was opposed to this idea and thought that the carbonates are secondary.

In the carbonatitic dykes of Alnö, also, carbonates are present, in many cases as a replacement product of the other minerals. Von Eckermann is of the opinion that this replacement was an autometasomatic process, which took place under conditions of falling temperature and pressure (Von Eckermann, 1948).

A similar mode of origin is also a possibility for the replaced kimberlite dykes of the Premier Mine. At the time of the formation of the dykes, a rest-magma may have been present which was rich in MgO, CaO, $CO_2$, FeO, and water and contained some $SiO_2$ and titanium and lesser amounts of $Al_2O_3$, $K_2O$, $Na_2O$, etc.

In the beginning and at relatively high temperatures, magnetite, olivine, perovskite, and ilmenite would crystallize out. During the later stages, when the temperature was below at least 750 degrees Centigrade, $Mg(OH)_2$ could have formed, and finally the calcite would crystallize out. During this period of waning temperature, the previously formed minerals might be partly or completely replaced by later products.

# CHAPTER VII

## THE RELATIONSHIP BETWEEN DIAMONDS, AND FRAGMENTAL AND INTRUSIVE KIMBERLITES

During this present investigation as much of the literature concerning kimberlite as could be located was read. Observations made by others, and indications at the Premier Mine, seemed to point to a very interesting, and possibly significant, relationship between diamonds and certain types of kimberlite.

Many writers make use of the term "hardebank" when referring to some types of kimberlite. This term was apparently first applied to a variety of kimberlite which would not disintegrate on prolonged exposure to the atmosphere.

It was possible, from the many descriptions, to correlate this type of kimberlite with the intrusive varieties. The term "blue ground" or "normal blue ground" usually, but not invariably, apply to the fragmental kimberlites. Using these terms, it would be possible to call the Micaceous, Carbonate-rich, and Blue-black intrusive kimberlites of the Premier Mine "hardebanks" (more correctly "hardebanke") and the rest "blue ground". It is interesting to find that Williams (1932, p. 229) mentions the Premier Mine as a particularly good example of a mine with "hardebank" kimberlite, which cuts in and out of the "blue ground".

Intrusive kimberlites in the Premier Mine, and evidently in other mines as well, appear later than most of the fragmental types into which they intrude.

So far for the introduction. The point which is to be emphasized here is the apparent poverty of these later kimberlites in diamonds.

While Williams never had a clear idea of the true difference between fragmental and intrusive kimberlites, he did comment on the relative lack of diamonds in the "hardebank" as compared to the "blue ground" (Williams, 1932).

Wagner also noted this difference in diamond content and stated: "Thus, the yield of the fragmental material, by which the Kimberley pipe was filled down to a depth of over 1,000 feet, was three times as high as that of the solid kimberlite exposed on the lower levels of the mine" (Wagner, 1914, p. 189).

Very few figures of actual diamond content are available to support this statement, but the following facts give evidence that it may be correct:

While sampling at the Premier Mine has not been completed yet, there are some indications that the area where the intrusive kimberlites occur is poorer in diamonds than the area where the outer zone of fragmental kimberlites is present. No actual figures are available, but during a period when the concentrates of the treatment plant contained numerous of the heavier fragments of the Micaceous and Carbonate-rich kimberlites, the yield of diamonds was much below the average yield of the mine.

Williams (1932) also mentions that the "snake rock" (an intrusive kimberlite dyke) of the De Beers Mine at Kimberley contained no diamonds, and that the "hardebank" kimberlite of the west end of the same mine could never be worked profitably.

From Du Toitspan Mine of Kimberley, the same author (Williams, 1932, p. 230) describes a fragmental kimberlite completely surrounded by two varieties of "hardebank" kimberlite. The fragmental kimberlite apparently extended as far as the 670-foot level only and, from the description, it seems clear that it was replaced by intrusive kimberlite on lower levels. This fragmental kimberlite yielded 35 carats per 100 loads (1 load = 1,600 pounds), while the narrow inner zone of "hardebank" yielded only 5 to 7 carats per 100 loads, and the outer zone was quite barren.

The inner zone of intrusive kimberlite may have obtained some, if not all, of its diamond content from mixing with the breccia.

The kimberlite from the Schuller Mine in the Pretoria district has been mentioned before, when it was correlated with the intrusive Blue-black kimberlite of the Premier Mine. Wagner (1914) states, moreover, that this pipe is completely occupied, from the surface down, by a plug of "hardebank". This kimberlite was extensively tested but, although some diamonds were found, it could never be developed into a paying proposition, which probably means that less than 6 carats per hundred loads were found. The Koffyfontein Mine in the Orange Free State yields 5 3/4 carats per 100 loads and this is probably near the limit for economic mining (Wagner, 1914, p. 138).

The kimberlite from Kleinzonderhout and Franspoort in the Pretoria district is described as "hardebank" by Williams (1932). Here, too, diamonds were either absent or present in very small quantities. There are more known occurrences of "hardebank" kimberlite which have a negligible or small diamond content, but the instances quoted will suffice.

In contrast to this apparent lack of diamonds in the intrusive kimberlites are the numerous occurrences of fragmental kimberlite which are being profitably mined at present.

Wagner, who also noted that fragmental kimberlites were, as a rule, richer in diamonds than the intrusive kimberlites, thought that this may be due to a concentration caused by the elimination of the less resistant constituents of kimberlite in the form of volcanic dust (Wagner, 1914, p. 169). While this explanation may be valid, in part, it still gives no reason why so many occurrences of intrusive kimberlite should be practically barren of diamonds.

The association of the diamond with the fragmental kimberlites needs an explanation, and a hypothesis to explain this is given in the following pages.

The association of the diamonds with the fragmental kimberlite must be connected with the fundamental question of the formation of the diamonds themselves, providing, of course, that the diamonds actually did form in the kimberlites. There is considerable evidence that the latter was actually the case.

It is a known fact that the physical characteristics of individual diamonds vary, and also that the characteristics of a group or "parcel" of diamonds from one kimberlite pipe will differ from that of a group taken from another pipe in the same vicinity (Wagner, 1914; Sutton, 1928).

In a few cases it is also found that "parcels" of diamonds from different kimberlites of the same pipe have different features (Melville, 1909).

In the light of this evidence and also of the fact that some of the kimberlite minerals have been found included in diamonds (Williams, 1932; Sutton, 1928; Wagner, 1914), it is logical to conclude that the diamonds crystallized out in the individual "fingers" of kimberlite only after these had left their source. The different physicochemical conditions prevailing in the different pipes, or at different times in the same pipe, might well cause different qualities, shapes, and sizes of diamonds to crystallize out. This is not a new idea and has already been brought forward by others (Wagner, 1914).

Since the chemical composition of the fragmental kimberlites does not differ very greatly from that of some of the intrusive kimberlites, it will be necessary to investigate the physical conditions of temperature and pressure under which these groups formed.

To find which of the two sets of conditions coincides most closely with the conditions required for the formation of the diamond, it will also be necessary to investigate the conditions under which this mineral could form.

Through the courtesey of Professor Buddington of Princeton University, the writer obtained a translation of a comparatively recent paper, "Synthetic Diamonds", by O. I. Leipunskii.

From a study of the thermodynamic properties of diamond and graphite, Leipunskii arrived at the conclusion that, for the formation of diamond, the crystallization must proceed as follows:

1) "At a pressure at which diamond is in a more stable phase than graphite.

2) "At a sufficiently slow speed so as not to favour graphite as the kinetically more probable phase.

3) "At such a temperature that it is possible to rearrange the crystal lattice so that, in the event that graphite is formed, it can be transformed into diamond.

"Rearrangement in the diamond lattice begins at 1,700 - 1,800 degrees Kelvin and at this temperature there is no reason to believe that the graphite lattice is the more stable. The temperature of 2,000 degrees Kelvin would therefore appear to be the minimum for obtaining diamond from graphite in the solid phase, so that the experiments must be carried out at a pressure at which diamond is, at this temperature, more stable than graphite, for example, at a pressure of the order of 60,000 atmospheres".

Leipunskii is furthermore of the opinion that this theoretical temperature and pressure of the formation of diamond could be reduced if the formation took place in a medium which can dissolve the solid phase. "Hence, if a medium could be selected in which the processes of the solution of graphite and of diamond went on fast enough at temperatures below 2,000 degrees Kelvin, then the diamond crystal would develop from the liquid phase at a pressure below 60,000 atmospheres" (Leipunskii, 1939).

Molten kimberlite is apparently a solvent of diamond and graphite. Luzi (1892) found that molten kimberlite readily dissolved diamond at 1,770 degrees Centigrade and Friedlander and Hasslinger (Doelter, 1912) found that carbon was soluble in molten kimberlite or its chemical equivalent. Unfortunately, it is not known what is the lowest temperature at which kimberlite could still dissolve these two forms of carbon. Due to the lack of suitable equipment, an experiment attempted by the writer was unsuccessful. It seems likely, though, that graphite and diamond may still be soluble at the temperature at which the kimberlite magma existed. The exact figure for this temperature is not known but 1,000 degrees Centigrade seems a reasonable estimate, since it was found that the powdered kimberlite melts at between

1,350 and 1,370 degrees Centigrade* and that the lower limit of magmatic temperature is, in some cases, 800 degrees Centigrade.

From the data supplied by Leipunskii (1939), it is clear that the pressure required to form diamond at 1,000 degrees Centigrade is 32,000 atmospheres.

It is also necessary now to compare the physical conditions of formation of the fragmental and intrusive kimberlites.

For the formation of a fragmental rock such as, for instance, the Normal kimberlite, a force is necessary which could cause the fragmentation of the rock as well as its upward movement in the crust, after or during fragmentation. An explosive force fulfils these requirements.

Laboratory studies have indicated that the crystallization of hydrous melts produces very high gas pressures, which are transmitted to the walls and roofs of containing chambers (Goranson, 1938).

It is more than likely such high gas pressures were present during the crystallization of the kimberlite magma which gave rise to the Normal kimberlite. At the moment this gas pressure overcame the weight and shearing strength of the overlying column of rock, an upward surge

* Melting temperatures were determined in the mining department of McGill University by the laboratory technician, Mr. A. Ward.

of gas must have taken place. The fast moving gas would carry with it fragments of already consolidated kimberlite, as well as portions of the magma, which would freeze immediately and probably also be fractured during the upward movement.

Evidence has already been cited to show that the explosive eruption of the Normal kimberlite started from below, or in, the Dolomite series of the Transvaal system. At the Premier Mine, this series lies at a depth of about 3 1/2 miles. At the time of the eruption, this formation must have been even farther below the surface, as an unknown amount of rock has since been removed by erosion.

When an attempt is made to calculate the value of the gas pressure required to fracture and lift a column of rock 3 1/2 miles thick, many unknown factors make this calulation nearly, if not actually, impossible.

Factors, which must be taken into consideration are:

1) The thickness of strata to be ruptured.

2) The size and configuration of the diatreme or pipe.

3) The shearing strength of the various rocks.

4) The way in which the rupture took place.

Of these factors, 1) can be determined approximately. In the case of 2) it is not certain, but it seems possible, that the pipe may be carrot-shaped, since some of the pipes in the Kimberley area which have been mined to great depths are of that shape (Wagner, 1914). 3) May be determined experimentally, but since this has not been done no figures are available. The evaluation of 4) leads to much speculation since factors such as the presence of strata with different shearing strengths, joints, bedding planes, and compressibility will all play an important role.

However, assuming that a cone of rock 3 1/2 miles high, and with a base of 1,000 feet was ruptured out of a homogeneous layer, and that the shearing strength of this rock is 100 $kg/cm^2$ (limestone has a shearing strength of 100 to 200 $kg/cm^2$), the calculated value for the required pressure is over a billion atmospheres.

This figure is certainly much too high, probably because the rupture does not take place in the assumed manner. However, even when the compressibility of the rock is taken into consideration, and it is assumed that shearing takes place progressively over short distances, the calculated values for the required gas pressure is still well over 32,000 atmospheres.

While no definite values can be obtained, the above discussion serves to indicate that gas pressures of 32,000 atmospheres were within the realm of possibility.

After the first fragmental kimberlites were emplaced, they were intruded by later kimberlites. The gas pressures in these later intrusions must have been moderate compared to those which ruptured the crust during the first phase of the volcanic activity. This would have to be the case, since the fragmental filling of the pipe would act as a safety-valve and would tend to keep the pressure moderate.

From this discussion it follows that the physicochemical conditions required for the formation of diamond were most likely met during the first phase of the volcanic activity, which gave rise to the kimberlite pipes. This adequately explains why diamonds are found associated particularly with the early fragmental kimberlites.

## Economic Value of this Hypothesis

Of the many kimberlite pipes so far discovered on the African continent, and elsewhere, only a small number contain any diamonds at all, and an even smaller number can be mined profitably. If the foregoing hypothesis is valid, then it follows that the careful mapping and systematic sampling of a kimberlite pipe will be necessary before it can be stated whether it will be a profitable undertaking to mine the deposit. This has apparently not been done in all cases in the past and it may well prove that portions of pipes, not mined at present, may contain a high enough percentage of diamonds to make them of economic value.

# CHAPTER VIII

## SUMMARY OF CONCLUSIONS

1) The Normal kimberlite was the first kimberlite to erupt and this eruption, which was probably in the form of a gaseous explosion, started from below, or in, the Dolomite series of the Transvaal system. Prior to this explosive eruption, the pressure in the magma built up gradually and finally reached a point where it was sufficient to rupture the overlying formations. If all the factors involved could be properly evaluated, the actual pressure reached could be calculated.

2) The Normal kimberlite was followed by the Blue-grey kimberlite, which was emplaced in a similar manner. During this eruption, fragments of the Blue-grey and Normal kimberlites intermingled in places to give rise to the Intermediate kimberlite.

3) The intrusion of the Blue-black kimberlite magma followed these explosive eruptions. On its way upward in the crust, the magma included and metamorphosed fragments of foreign rock. The magmatic temperature was most likely above 800 degrees Centigrade.

4) After the intrusion of the Blue-black kimberlite magma, the vent was apparently sealed up sufficiently for pressure to build up in later intrusions. The release of this pressure was upward and it caused fragmentation of the intrusives or the overlying kimberlites, forming, in two successive stages, the Western and Eastern fragmental kimberlites.

5) The intrusion of the Micaceous kimberlite magma followed. The temperature of this magma was, like that of the Blue-black kimberlite magma, probably above 800 degrees Centigrade.

6) The Carbonate-rich kimberlite magma intruded in a number of stages. During the first stage, portions of the already consolidated Micaceous kimberlite were fractured and assimilated. At a slightly later stage, after the consolidation of the mixture of Micaceous and Carbonate-rich kimberlite, another portion of this magma welled up and froze as a tapering mass, which appears as a dyke on all levels except the 1,060-foot level. Like the other intrusive kimberlites, the magmatic temperature of the Carbonate-rich kimberlite is also judged to have been above 800 degrees Centigrade.

7) A progressive enrichment in lime is apparent in the successive generations of kimberlite at the Premier Mine. This may be due to one of two, or to a combination of the two, factors. These are:

a) The inclusion and absorption of limestone.

b) A normal trend in the differentiation of ultrabasic magmas.

8) Kimberlites, in general, may not necessarily have had a completely vitreous groundmass, as is supposed by some authors. Some of the alteration products of normal kimberlite minerals, especially phlogopite, may confuse this issue.

9) The final phase of the magmatic activity at the Premier Mine is probably represented by the replaced kimberlite dykes.

Most likely these dykes were originally similar to kimberlite in nature but they are now largely replaced by magnetite, calcite, and colloidal or amorphous magnesium hydroxide. This replacement may have been hydrothermal or deuteric.

10) The early fragmental products of the kimberlite pipes apparently are the rocks in which diamonds are found in greatest concentration. The reason for this is that, during the early phase of igneous activity, physicochemical conditions were favourable for the formation of the diamond.

## Recommendation For Further Work

The genesis and differentiation of the kimberlite magma is still an open question, the complete answer to which must await further and more detailed investigation. A fair number of chemical analyses of kimberlite of various types are in existence. These, however, only indicate the chemical composition of the rocks as they are now. Before these chemical analyses can be used with any degree of success, it will be necessary to study the alteration, and the alteration products, of kimberlite in more detail. Since ordinary petrographic methods are insufficient for such a study, other means must be adopted. Differential thermal analyses may be one method of attacking the problem.

A detailed study of a kimberlite pipe containing kimberlites of different types and ages, and occurring in a region free from limestone, would perhaps throw additional light on the differentiation of kimberlite, especially on the variation of the lime content of the different varieties of kimberlite.

To answer the question why diamonds are mainly associated with ultrabasic rocks like the kimberlite, it may be necessary to undertake detailed experiments, for instance on the solubility of graphite and diamond in rock-melts of various compositions.

# BIBLIOGRAPHY


BARTH, T.F.W. (1948), Oxygen in Rocks:- a Basis for Petrographic Calculation, jnl. Geol. vol. 56, pp. 50-60, 1948.

BENSON, W.N. (1915), The Origin of Serpentine, a Historical and Comparative Study, Am. Jnl. Sci., 4th Ser., vol. xlvi, pp. 693-731, 1915.

BONNEY, T.G. (1897), On Some Rock Specimens from Kimberley, South Africa, Geol. Mag. 1897, pp. 448-453 and 497-502.

BONNEY, T.G. (1907), On the Supposed Kimberlite Magma and Eclogite Concretions, Proc. and Tr. Geol. Soc. S.A. 1907, pp. 95-100.

BOWEN, N.L. (1924), The Fen Area, Norway, Am. Jnl. Sci., 5th Ser., vol. 8, pp. 1-11, 1924.

BRÖGGER, W.C. (1921), Die Eruptivgesteine des Kristianagebietes, IV - Das Fengebiet in Telemark, Norwegen, Vid. Selsk. Skr., 1, kl. 9, 1921.

CORSTOPHINE, G.S. (1907), The Occurrence in Kimberlite of Garnet-Pyroxene Nodules carrying Diamonds, Trans. and Proc. Geol. Soc. S.A. 1907, pp. 65-68.

DALY, R.A. (1925), Carbonate Dikes of the Premier Diamond Mine, Transvaal, Jour. Geol., vol. 33, 1925.

DAUBREE, M. (1890), Recherches expérimentales sur le role possible des gaz a hautes temperatures, doues de trés fortes pressions et animés d'un mouvement fort rapide, dans divers phénomènes Géologiques, Bull. Soc. Geol. Fr. (3) XIX, pp. 313-354, 1890-1891.

DAVIES, K.A. (1947), The Phosphate Deposits of the Eastern Province, Uganda, Econ. Geol. XLII, 2, pp. 137-146, 1947.

DOELTER, C. (1912), Handbuch der Mineralchemic, 1912.

DUNN, E.J. (1874), On the Mode of Occurrence of Diamonds in South Africa, Q. Jnl. Geol. Soc., (London), vol. XXX, pp. 54-60, 1874.

DU TOIT, A.L. (1906), Geological Survey of the Eastern Portion of Griqualand West, 11th Rept. Geol. Comm. C. Colony, pp. 89-176, 1906.

DU TOIT, A.L. (1939), Geology of South Africa, 2d-ed., Edinburgh, 1939.

GORANSON, R.W. (1938), Silicate-water systems: Phase equilibria in the $NaAlSi_3O_8$-$H_2O$ and $KAlSi_3O_8$-$H_2O$ systems at high temperatures and pressures, Am. Jnl. Sc. 5th ser., vol. 35A, pp. 71-92.

HALL, A.L. (1904), Über einige neue Diamantlagerstätte Transvaals, Zeits. prk. Geol. XII, pp. 193-199, 1904.

HALL, A.L. (1932), The Bushveld Igneous Complex of the Central Transvaal, S.A. Geol. Surv. Mem., 28, 1932.

HARGER, H.S. (1907), Discussion on the Papers of Corstophine and Voit, Proc. Geol. Soc., S.A., 1907.

HESS, H.H. (1933), The Problem of Serpentinization and the Origin of certain Chrysotile Asbestos Talc and Soapstone deposits, Econ. Geol., vol. XXVIII, pp. 634-657, 1933.

HOLMES, A. (1921), Petrographic Methods and Calculations, Murby and Co., London, 1921.

HOLMES, A. (1936), A Contribution to the Petrology of Kimberlite and its Inclusions, Geol. Soc., S.A. Trans. 39, pp. 379-427, 1936.

KYNASTON, H. (1929), The Geology of the Counry Surrounding Pretoria, an Explanation of Sheet 1 (New Series). Revised by Krige, L.J. and Lombaard, B.V. The Geological Survey of the Union of South Africa, Pretoria, 1929.

LEIPUNSKII, O.I. (1939), Ob Iskusstzennykh Almazakh, ("Synthetic Diamonds"), Uspekhi Khimii (Moscow), vol. 8, pp. 1519-34, 1939.

LEWIS, H.C. (1897), Papers and Notes on the Genesis and Matrix of the Diamond. Edited by T.G. Bonney, Longmans Green and Co., London, 1897.

LUZI, W. (1892), Uber Künstliche Corrosionsfiguren an Diamanten, Ber. d. Deutsch. Chem. Gesellsch, 1892.

MELVILLE, E.H.V. (1909), Note on the Roberts Victor Mine, Trans. Geol. Soc., S. Afr., 1909.

MENNELL, F.P. (1946), Ring Structure with Carbonate Cores in Southern Rhodesia, Geol. Mag., LXXXIII, 3, pp. 137-140, 1946.

MERWIN, H.E. (1915), U.S. Geol. Surv. Prof. P. 87, 1915.

OSBORNE, E.F. (1943), The Compound Merwenite ($3CaO.MgO.2SiO_2$) and its Stability Relations within the System $CaO-MgO-SiO_2$, (Preliminary report), Jnl. Am. Ceram. Soc. vol. 26, No. 10, 1943.

PARTRIDGE, F.C. (1934), The Identification of Kimberlite and Kimberlite Minerals by Spectroscopic and other Methods, Geol. Soc. So. Afr. Trans. 37, pp. 205-211, 1934.

ROGERS, A.F. (1918), An American Occurrence of Periclase and its Bearing on the Origin of Calcite-brucite Rocks. Am. Jnl. Sc., Ser. 4, vol. 46, pp. 581-586, 1918.

ROGERS, A.F., and KERR, P.F. (1933), Thin-section Mineralogy, McGraw-Hill Book Co., New York, 1933.

RODGERS, J. (1940), Distinction between Calcite and Dolomite on Polished Surfaces, Am. Jnl. Sc. 238, pp. 788-798, 1940.

SELFRIDGE, G.C. (1936), An X-ray and Optical Investigation of the Serpentine Minerals, Am. Min., vol. 21, pp. 463-501, 1936.

STRAUSS, C.A. and TRUTER, F.C. (1950), The Alkali Complex at Spitskop, Sekukuniland, Eastern Transvaal, Trans. Geol. Soc., So. Afr., 1950.

SUTTON, J.R. (1928), Diamond, a Descriptive Treatise, Thomas Murby and Co., London, 1928.

TALJAARD, M.S. (1936), South African Melilite Basalts and their Relations, Tr. Geol. Soc., So. Afr., vol. 39, 1936.

TOMKEIEFF, S.I. (1938), The Role of Carbon Dioxide in Igneous Magma, Brit. Assoc. Adv. Sci. Secn. C., pp. 417-418, 1938.

TURNER, F.J. (1948), Mineralogical and Structural Evolution of the Metamorphic Rocks, G.S.A. Mem. 30, 1948.

VAN BILJON, S.J. (1949), Transformation of the Pretoria Series, Geol. Soc., S. Afr., 1949.

VOIT, F.W. (1907), Kimberlite Dykes and Pipes, Tr. Proc. Geol. Soc., So. Afr., vol. 10, 1907.

VON ECKERMANN, H. (1948), The Alkaline District of Alnö Island, Sveriges Geologiska Undersökning, Ser. Ca., No. 36, 1948.

WANATABE, Takeo (1935), On the Brucite-marble (predazzite) from the Nantei Mine, Suian, Tyôsen (Korea). The geology of the Suian gold mng. dist. 1st. report, Journ. Fac. Sci., Hokkaidô Imp. Univ. Ser. 4, 1935. (Abstract in Min. Mag. Abstracts 6).

WAGNER, P.A. (1909), Petrographical Notes on the Kimberlite Occurrences in the Pretoria District. Tr. and Proc. Geol. Soc., S.A., vol. 14, pp. 43-63, 1911.

WAGNER, P.A. (1914), The Diamond Fields of Southern Africa, Johannesburg, 1914.

WAGNER, P.A. (1928), The Evidence of the Kimberlite Pipes on the Constitution of the Outer Part of the Earth, S.A. Jnl. Sci., vol. XXV, 1928.

WILLIAMS, A.F. (1932), The Genesis of the Diamond, 2 vols. London, 1932.

WILLIAMS, G.J. (1939), The Kimberlite Province and Associated Diamond Deposits of Tanganyika Territory, Bull. No. 12, Tang. Terr. Dept. of Lands and Mines, Geol. Div., 1939.

WINCHELL, A.N. (1947), Elements of Optical Mineralogy, Pt. II, John Wiley and Sons, New York, 1947.

PLATE I.

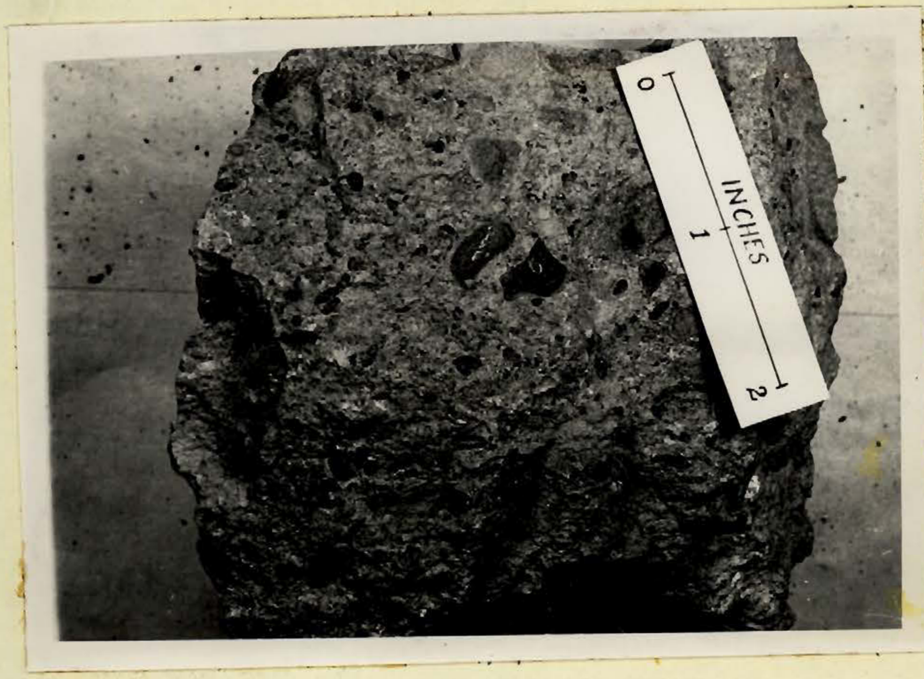



Figure 1. The Normal Kimberlite.

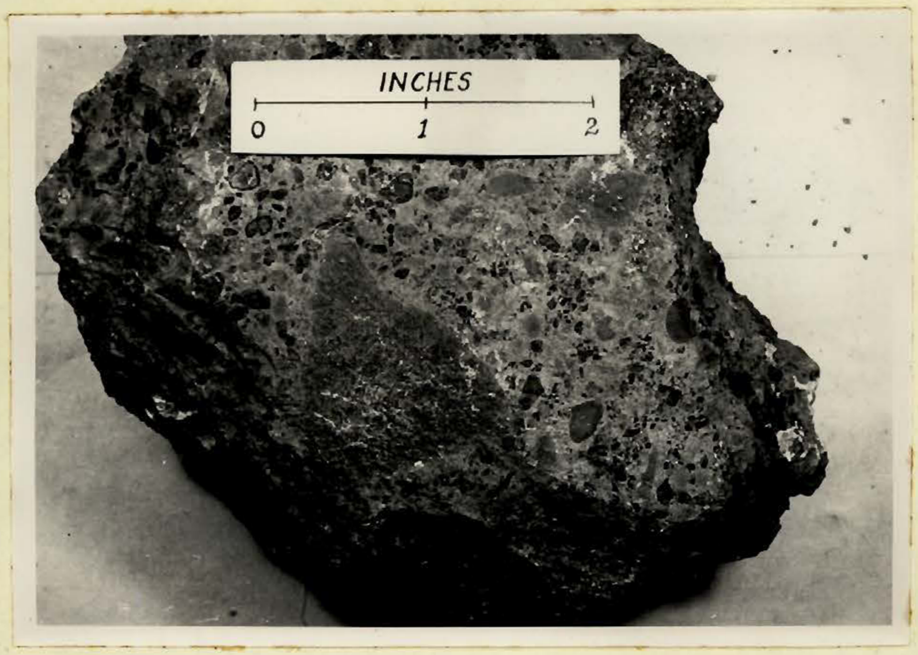



Figure 2. The Blue-grey fragmental Kimberlite.

PLATE II.


Figure 1. The Western-fragmental Kimberlite.


Figure 2. The Eastern-fragmental Kimberlite.

PLATE III.


Figure 1. The Blue-black intrusive Kimberlite.

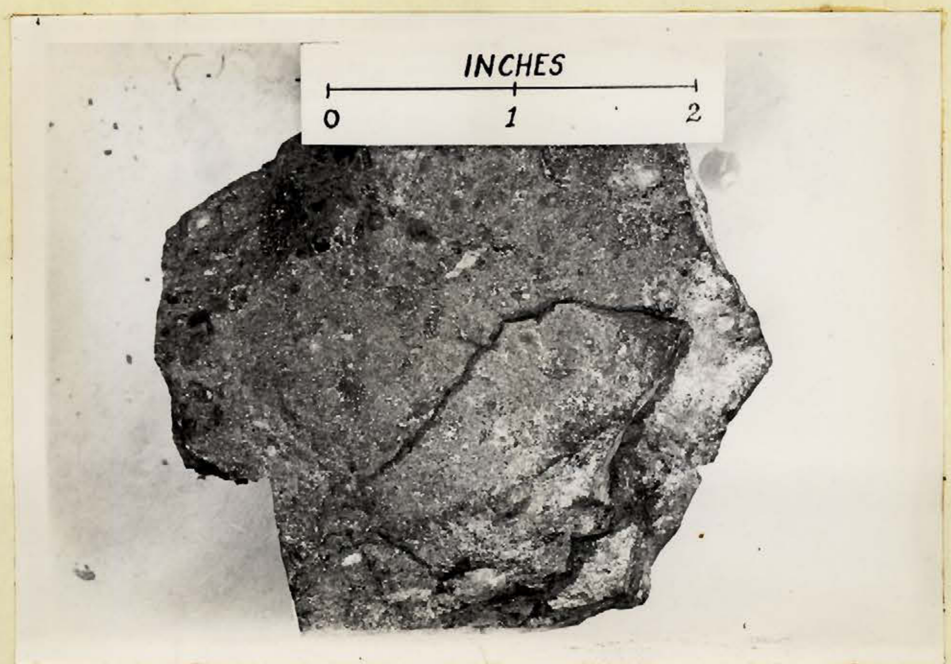



Figure 2. The Micaceous Kimberlite.

PLATE IV.

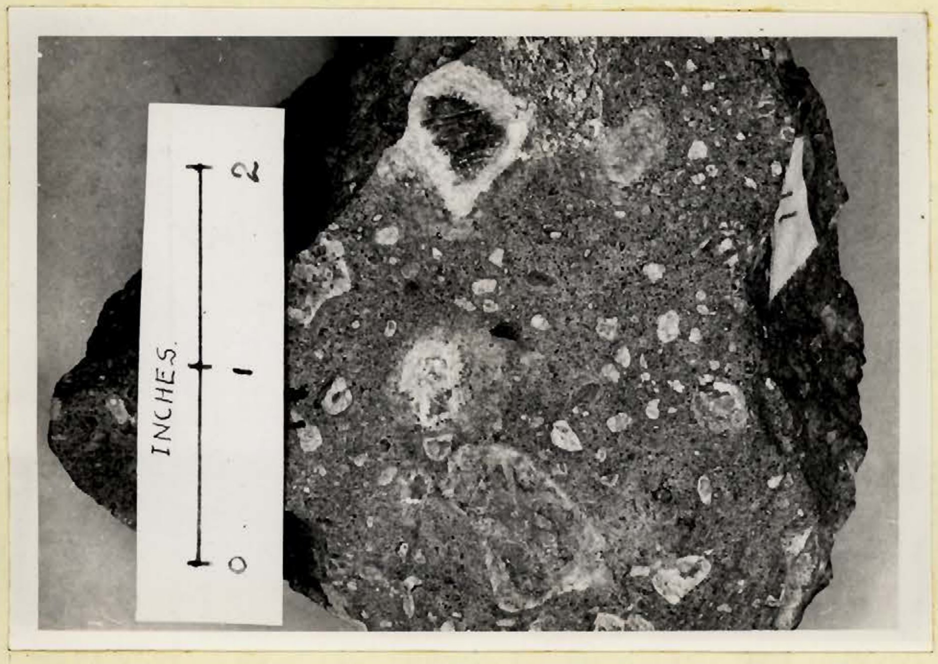



Figure 1. The Carbonate-rich Kimberlite.


Figure 2. Partly replaced kimberlite dyke. Note flow structure.

PLATE V.

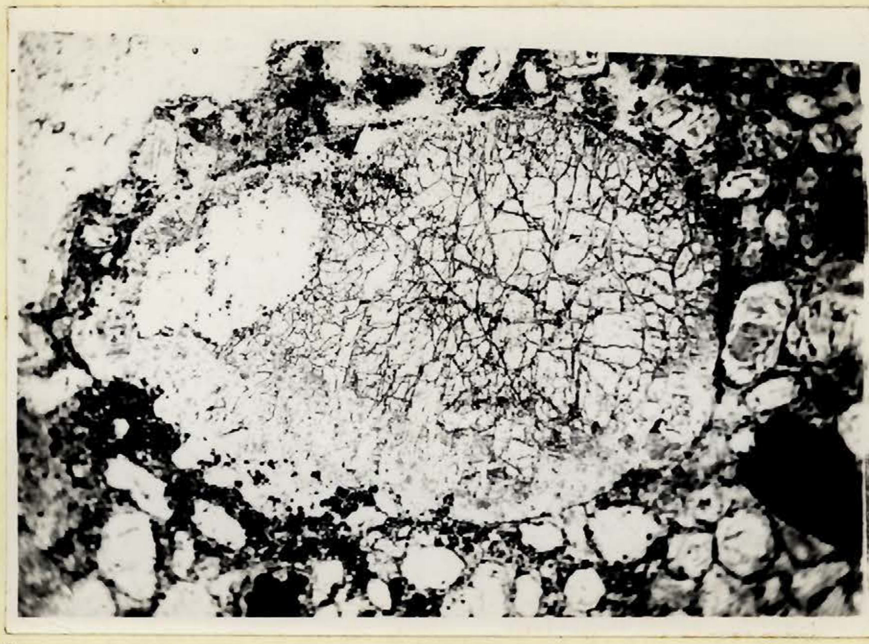


Figure 1. Large anhedral grain of olivine, surrounded by smaller idiomorphic olivine crystals. ( x 25 ) Ordinary light.

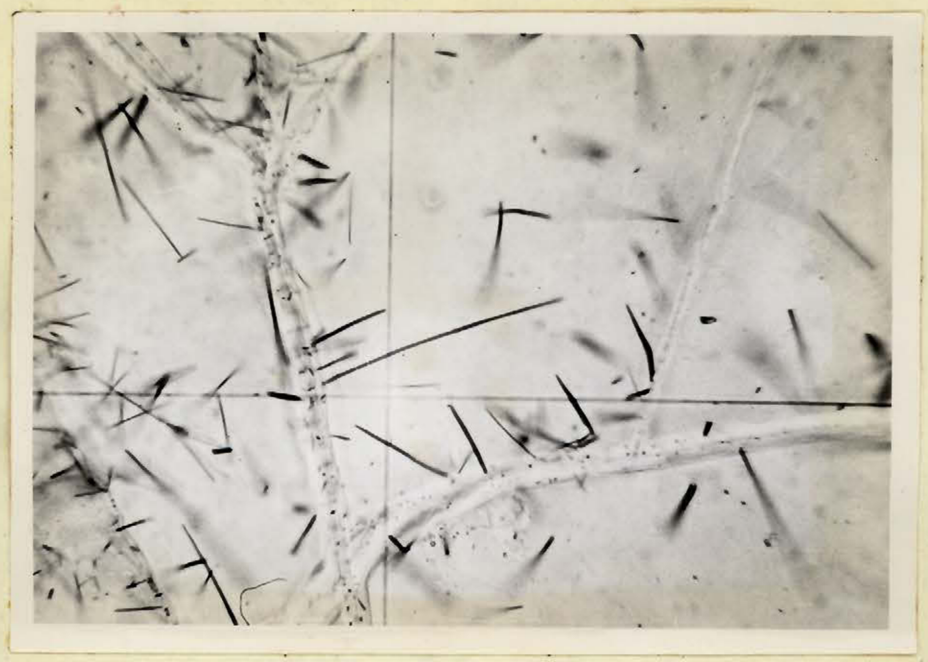


Figure 2. Rutile needles in serpentine. Ordinary light. ( x 320 )

PLATE VI.

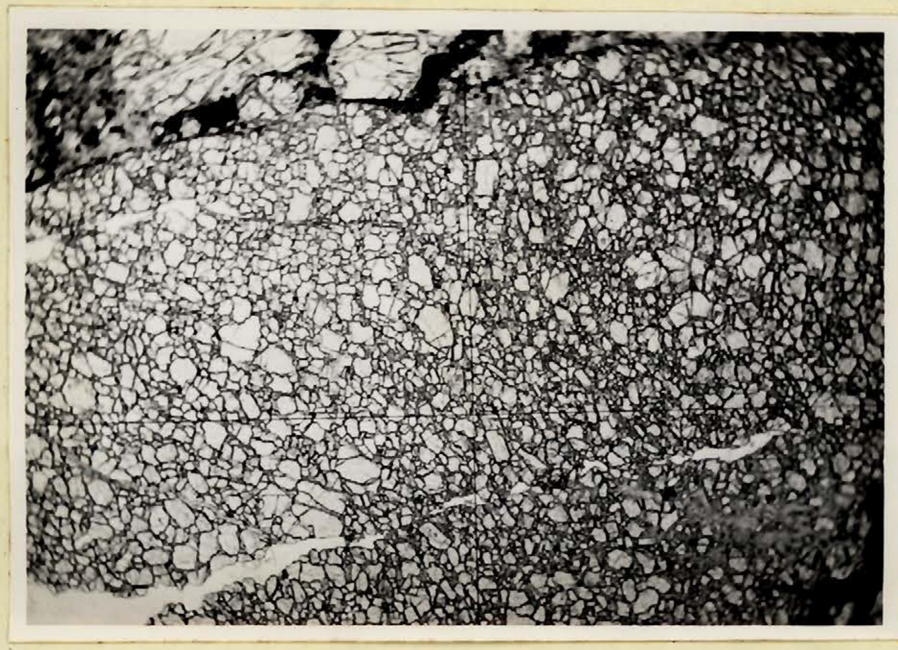


Figure 1. Polysomatic aggregate of olivine grains. Ordinary light. ( x 25 )

Figure 2. Polysomatic aggregate of olivine grains. Crossed nicols. ( x 25 )

PLATE VII.

Figure 1. Brown fibrous mineral developing in olivine. Ordinary light. ( x 90 )

Figure 2. Serpentine with "mesh" structure. Crossed nicols. ( x 25 )

PLATE VIII.

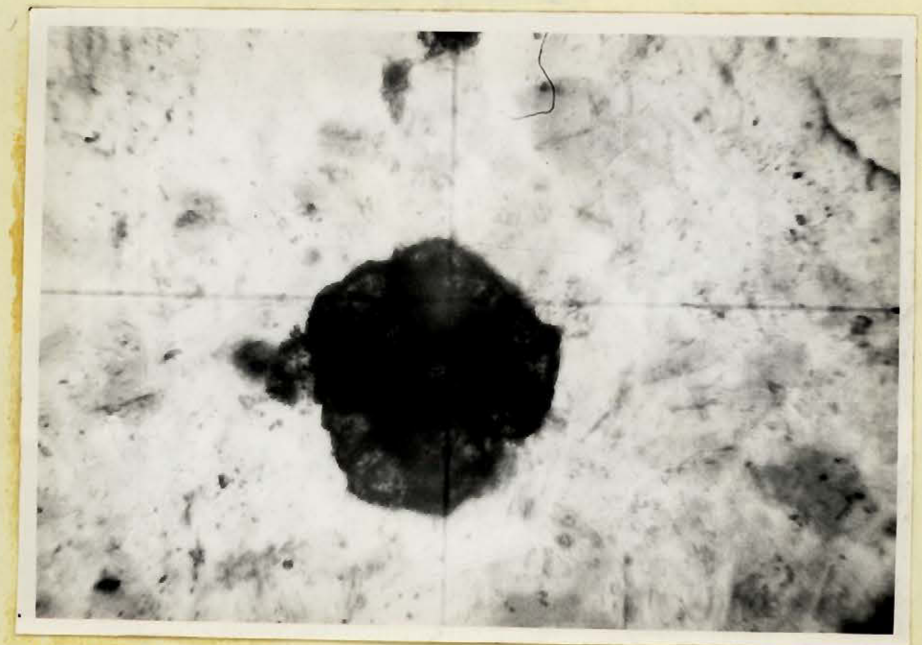


Figure 1. Twinned crystal of perovskite. Note the small re-entrant angles. Ordinary light. ( x 320 )

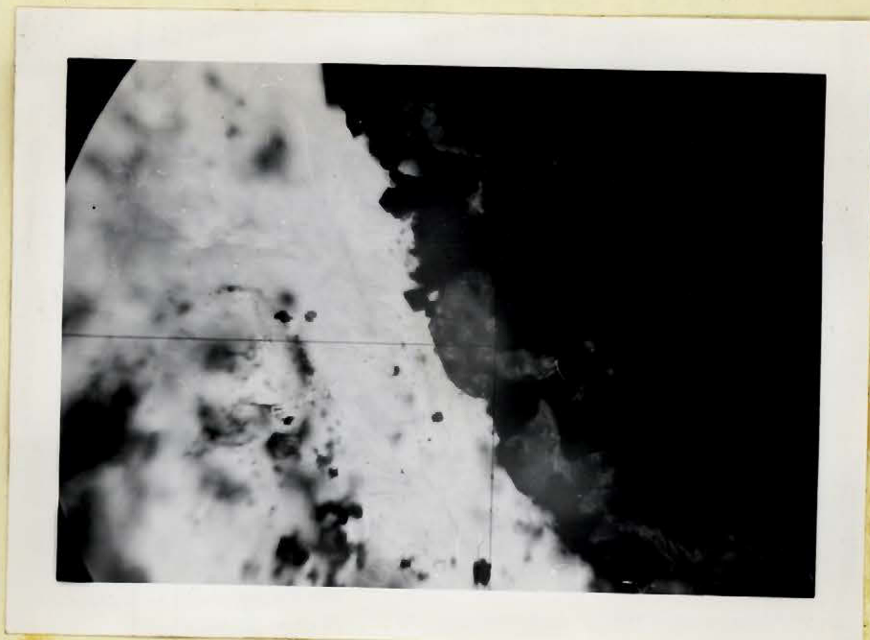


Figure 2. Ilmenite ( opaque ) altering to perovskite ( faintly transparent ). Ordinary light. ( x 300 )

PLATE IX.

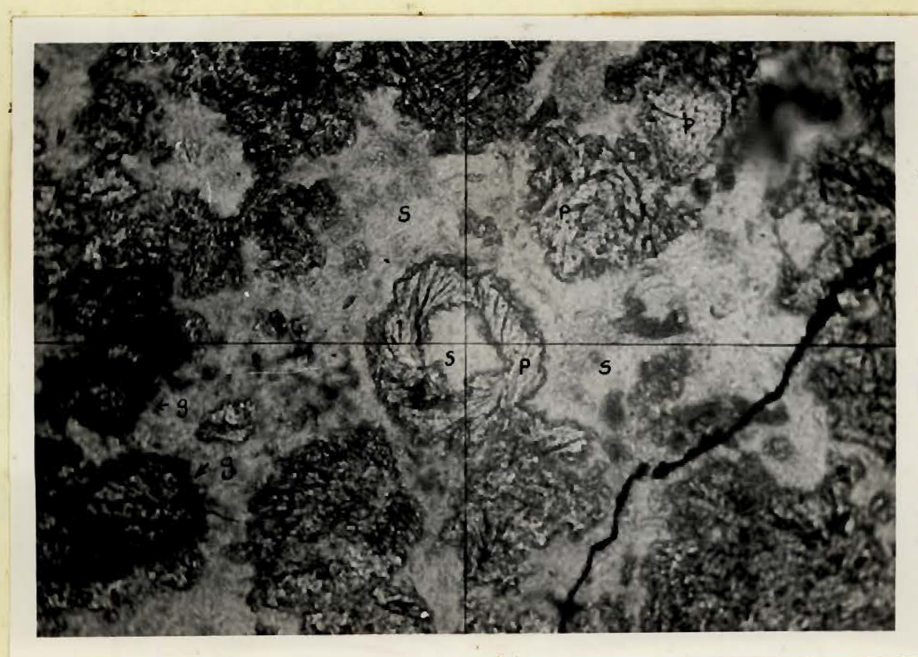


Figure 1. Completely metamorphosed inclusion, showing pyroxene ( p ) serpentine ( s ) and garnet ( g ). Ordinary Light. ( x 90 )

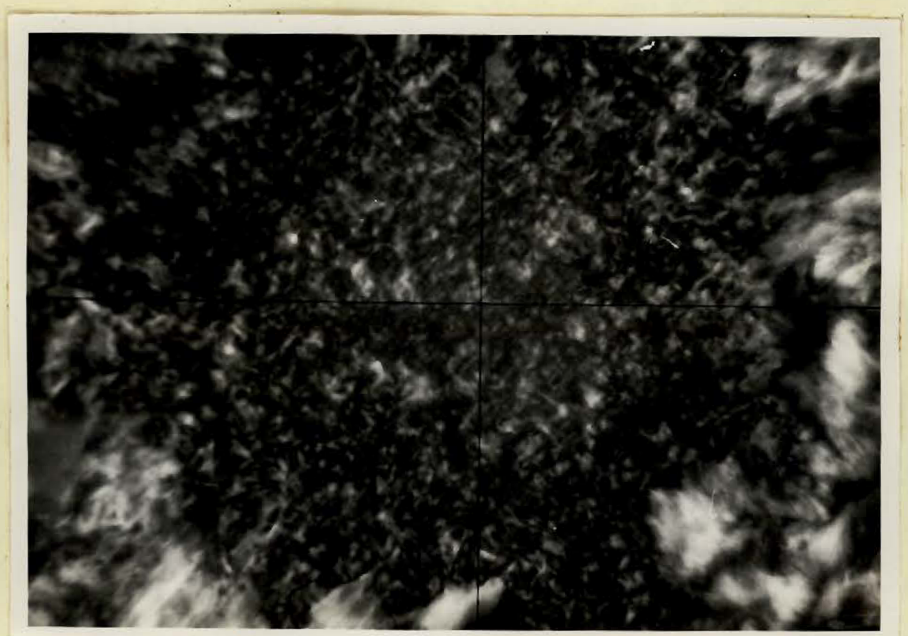


Figure 2. Antigorite. Crossed nicols. ( x 300 )

PLATE X.

Figure 1. Sphene, occurring as inclusions in and wreaths around altered olivine crystal. Ordinary light. ( x 90 )

Figure 2. Reaction rim of garnet, showing an outer zone of magnetite and narrower fibrous inner zones. Ordinary light. ( x 25 )

PLATE XI.

Figure 1. Pyroxene (p) and serpentine (s) formed from inclusions of limestone. Ordinary light. ( x 90 )

Figure 2. The Carbonate-rich Kimberlite, showing the nearly opaque periclase (?) in the groundmass. Ordinary light. ( x 90 )

PLATE XII.

Figure 1. Showing the fragmental nature of the Blue-grey Kimberlite. Ordinary light. ( x 25 )

Figure 2. Fragment of ilmenite, with the original ground-mass still adhering to it in places. Ordinary light. ( x 25 )

PLATE XIII.

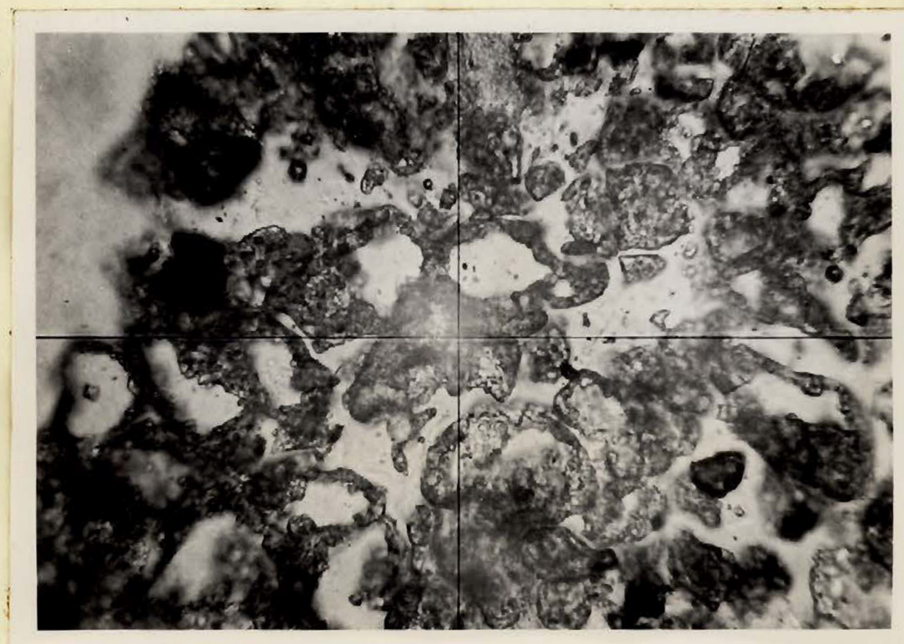


Figure 1. The periclase (?) of the Carbonate-rich Kimberlite under high magnification. ( x 320 ) Ordinary light.

PLATE XIV.

Figure 1. Talc ( white ) replacing serpentine ( dark ). Crossed nicols. ( x 90 )

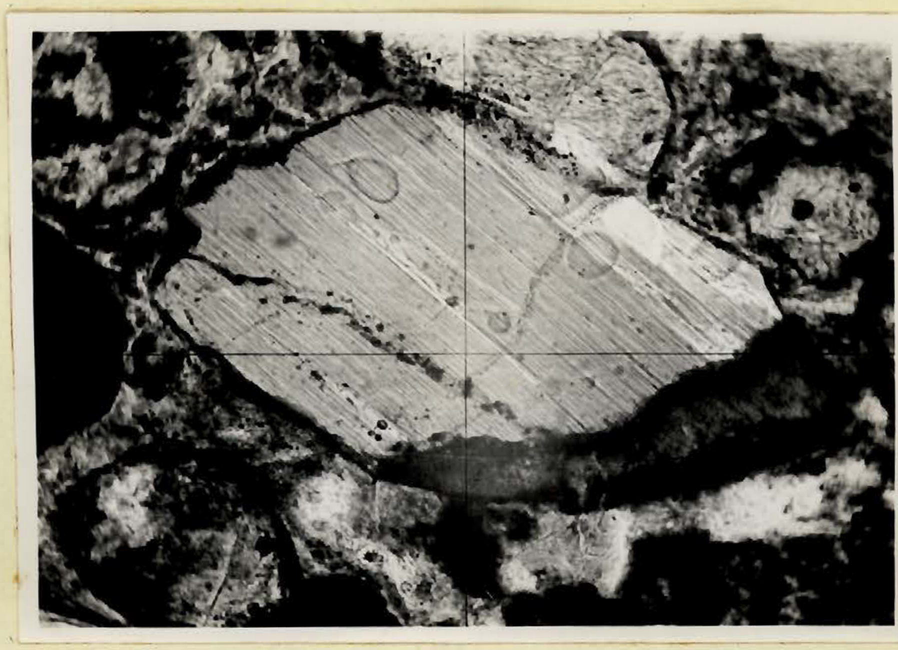


Figure 2. Hypersthene, showing reaction rim. Ordinary light. ( x 90 )

PLATE XV.


Figure 1. Olivine, altered to antigorite (a) and talc (t). The antigorite is largely replaced by calcite (c). Ordinary light. ( x 90 )

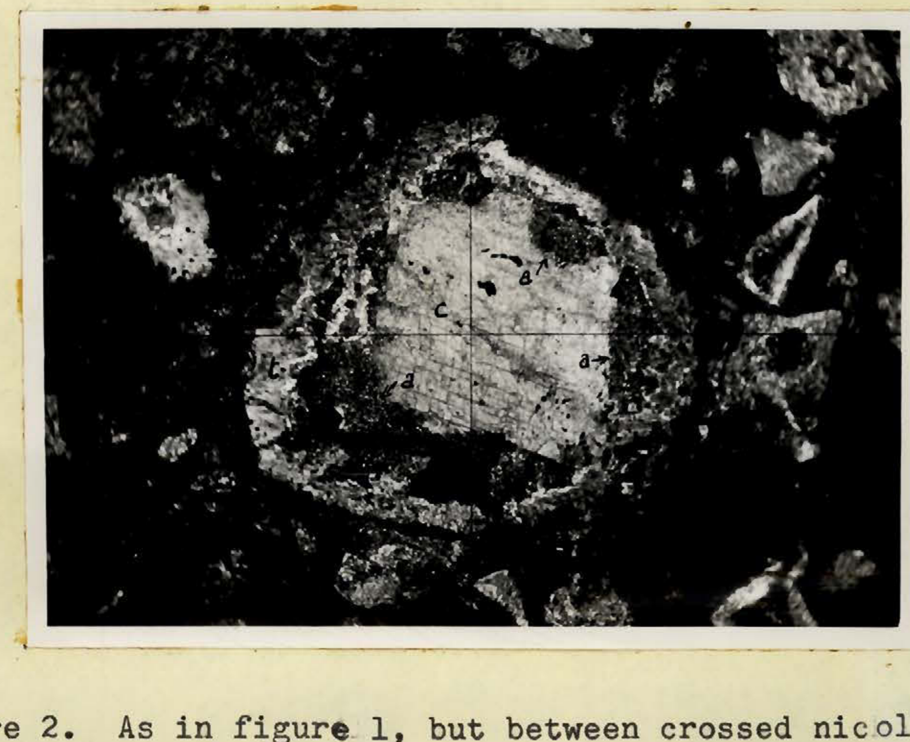



Figure 2. As in figure 1, but between crossed nicols. ( x 90 )

PLATE XVI.


Figure 1. View of partly replaced dyke rock, showing serpentinized olivines surrounded by calcite (c) and magnetite grains in the colloidal matrix. ( x 90 ) Ordinary light.

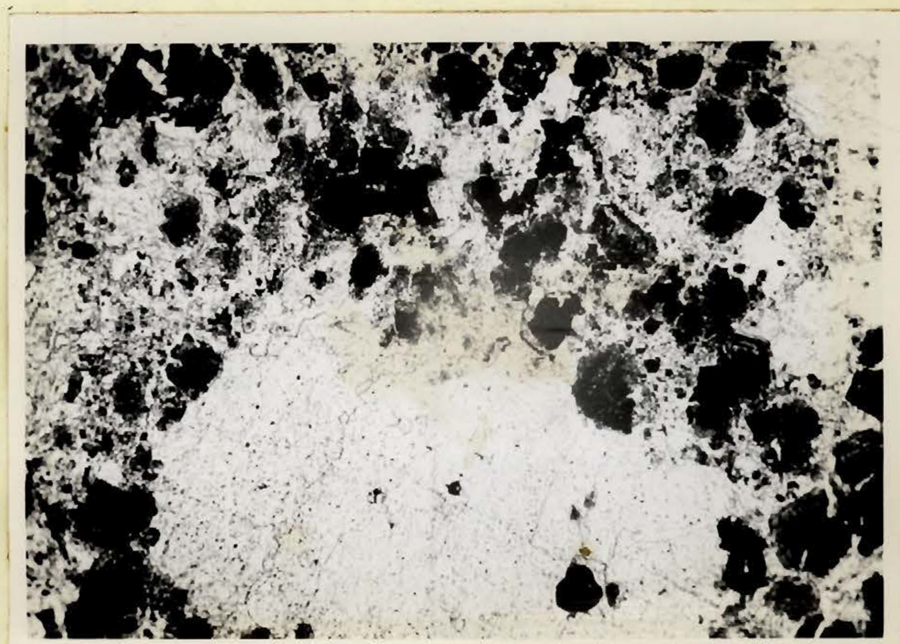


Figure 2. General view of the completely replaced dyke rock. The large clear areas are mostly calcite. The opaque grains are magnetite. ( x 90 ) Ordinary light.

PLATE XVII.

Figure 1. Magnetite pseudomorph after olivine ( in centre of photo ). ( x 90 ) Ordinary light.

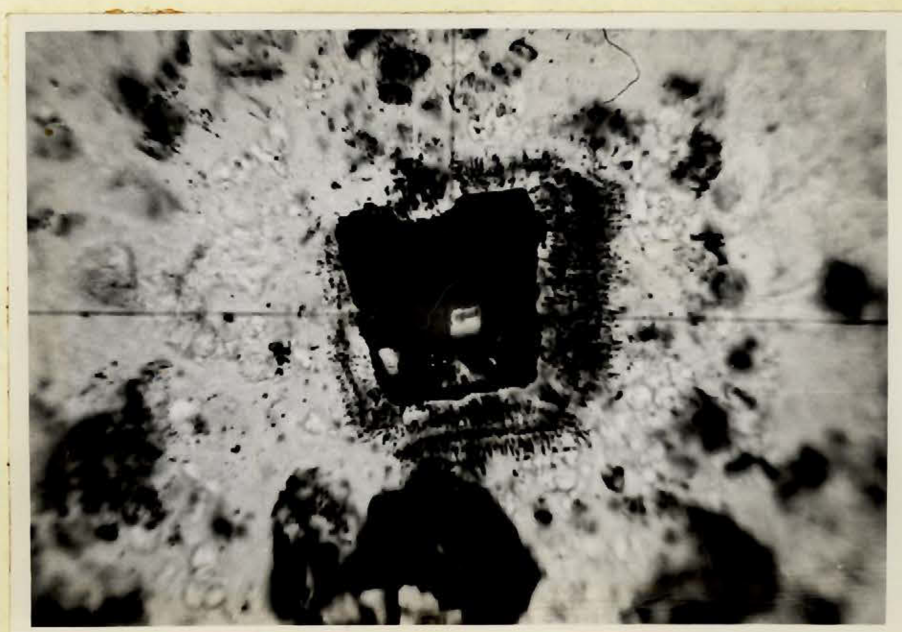


Figure 2. Solid core of magnetite surrounded by fine particles of the same mineral. ( x 320 ) Ordinary light.

PLATE XVIII.

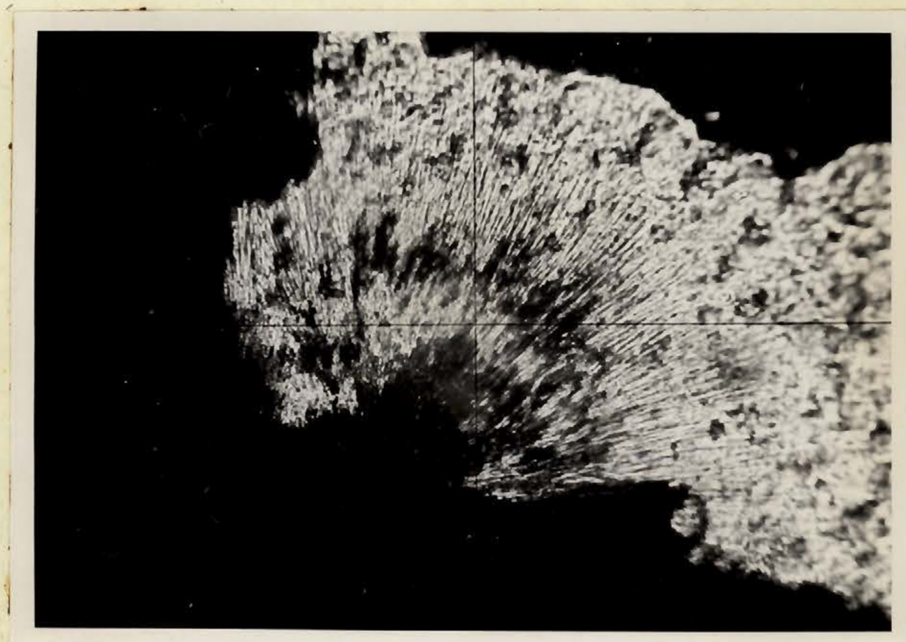
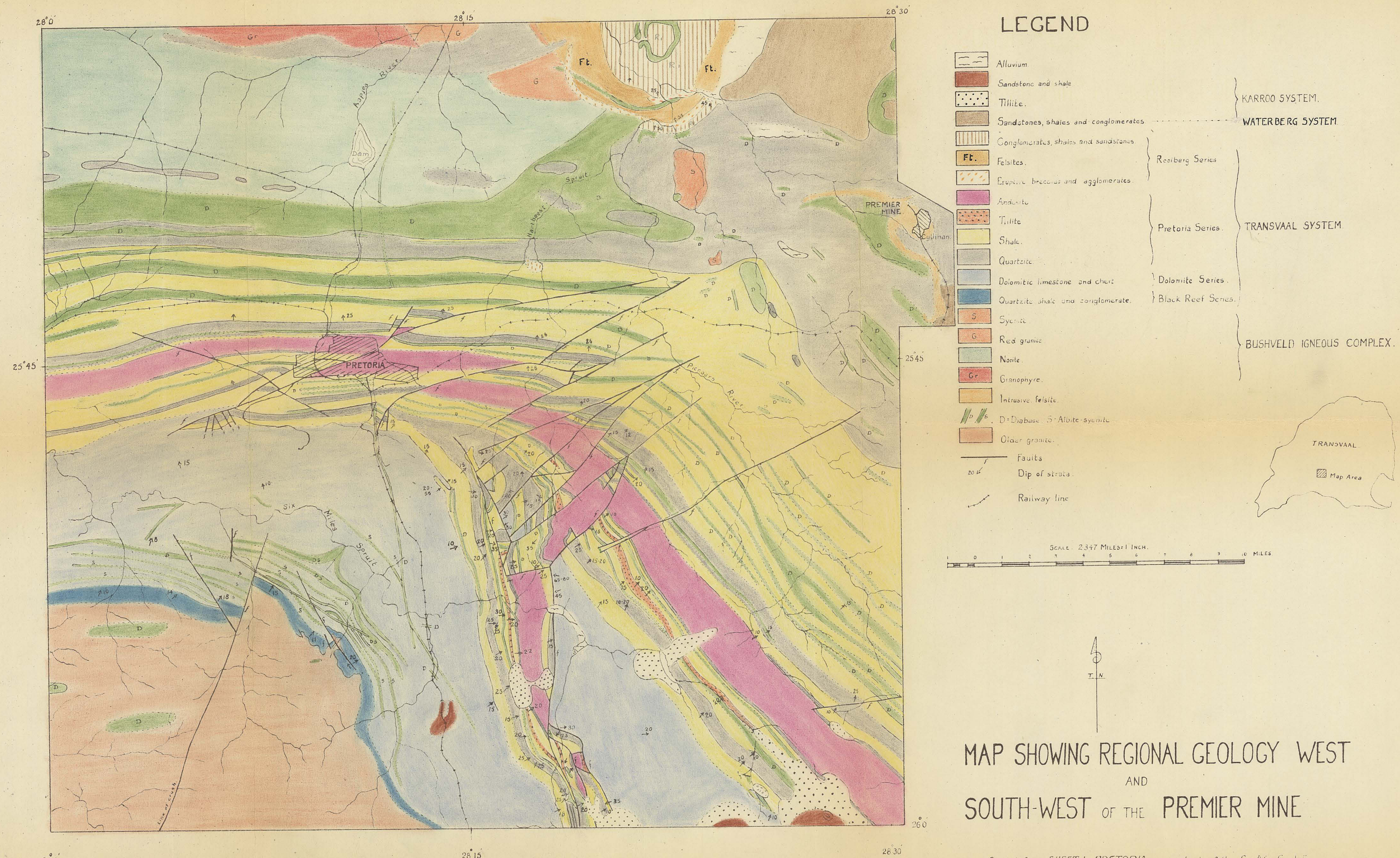


Figure 1. Radiating structure in calcite from a partly replaced dyke rock. ( x 300 ) Crossed nicols.




MAP SHOWING REGIONAL GEOLOGY WEST AND SOUTH-WEST OF THE PREMIER MINE

Copied from SHEET 1 - PRETORIA map sheet of the So. Afr. Geol. Surv.


PREMIER TVL. DIAMOND MINING CO. LTD.
SECTION A-B.
SCALE 1:1000
50
0
100
200
300
LEGEND.
Replaced Kimberlite Dykes.
Mixed zone of Micaceous and Carbonate-rich Kimberlite.
Carbonate-rich Kimberlite.
Micaceous Kimberlite.
Western-fragmental Kimberlite.
Eastern-fragmental Kimberlite.
Blue-black Kimberlite.
Blue-grey Kimberlite.
Intermediate Kimberlite.
Normal Kimberlite.
Normal Kimberlite with numerous quartzite inclusions.
Waterberg Quartzite.
Felsite.
A
B
Surface
Surface
Surface of open pit.
Surface of open pit.
LEVELS.
560'
610'
660'
710'
760'
810'
843'
890'
1060'


PREMIER TVL. DIAMOND MINING CO. LTD.
610' LEVEL.
SCALE 1:1000.
No 1 Vertical Shaft
Tunnels
Mains
No 1 Blue Shaft
Hoist Chamber
Surface Rim of the pipe.
LEGEND.
Replaced Kimberlite Dykes.
Mixed zone of Micaceous and Carbonate-rich Kimberlite.
Carbonate-rich Kimberlite.
Micaceous Kimberlite.
Western-fragmental Kimberlite.
Eastern-fragmental Kimberlite.
Blue-black Kimberlite.
Blue-grey Kimberlite.
Intermediate Kimberlite.
Normal Kimberlite.
Normal Kimberlite with numerous quartzite inclusions.
Waterberg Quartzite.
Diorite.
Felsite.
Geology by: A.E. Waters, C.G Stocken and E. Gerryts.
18.1.49.


PREMIER TVL. DIAMOND
MINING CO. LTD.
660' LEVEL
50' 0' 100' 200' 300'
SCALE 1:1000
LEGEND.
Replaced Kimberlite Dykes.
Mixed zone of Micaceous and Carbonate-rich Kimberlite.
Carbonate-rich Kimberlite.
Micaceous Kimberlite.
Western-fragmental Kimberlite.
Eastern-fragmental Kimberlite.
Blue-black Kimberlite.
Blue-grey Kimberlite.
Intermediate Kimberlite.
Normal Kimberlite.
Normal Kimberlite with numerous quartzite inclusions.
Waterberg Quartzite.
Felsite.
- Tunnels -
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
32
24
18
14
7
0
- Mains -
No 1 Sub Vertical Shaft.
No 1 Blue Shaft.
T.N.
+12,000
-99000
+11000
+12000
+13,000
-99000
Surface rim of the pipe


PREMIER TVL. DIAMOND MINING CO. LTD.
710' LEVEL
50 0 100 200 300
SCALE 1:1000.
+12,000
-11,000
-98,000
I.N.
Surface Rim.
Tunnels.
0 3 6 9 12 15 18 21 24 27 30 33 36 39 42 45
42
32
24
18
14
7
0
Mains.
No 1 Sub-Vertical Shaft.
No 1 Blue Shaft.
A
B
-99,000
+12,000
Surface Rim of the pipe.
+13,000
-99,000
LEGEND.
Replaced Kimberlite Dykes.
Mixed zone of Micaceous and Carbonate-rich Kimberlite.
Carbonate-rich Kimberlite.
Micaceous Kimberlite.
Western-fragmental Kimberlite.
Eastern-fragmental Kimberlite.
Blue-black Kimberlite.
Blue-grey Kimberlite.
Intermediate Kimberlite.
Normal Kimberlite.
Normal Kimberlite with numerous quartzite inclusions.
Waterberg Quartzite.
Felsite.
E.G.
18.1.49.


PREMIER TVL. DIAMOND
MINING CO. LTD.
760' LEVEL
50' 0' 100' 200' 300'
SCALE 1:1000.
LEGEND.
Replaced Kimberlite Dykes.
Mixed zone of Micaceous and Carbonate-rich Kimberlite.
Carbonate-rich Kimberlite.
Micaceous Kimberlite.
Western-fragmental Kimberlite.
Eastern-fragmental Kimberlite.
Blue-black Kimberlite.
Blue-grey Kimberlite.
Intermediate Kimberlite.
Normal Kimberlite.
Normal Kimberlite with numerous quartzite inclusions.
Waterberg Quartzite.
Felsite.
- Tunnels -
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45.
- Mains -
32
24
18
14
7
0
No 1 Sub Vertical Shaft.
No 1 Blue Shaft.
Surface rim of the pipe.
N
+12000
-98000
+11000
+13000
-99000
+12000


PREMIER TVL. DIAMOND MINING CO. LTD.
810' LEVEL.
50' 0 100' 200' 300'
SCALE 1:1000.
LEGEND.
Replaced Kimberlite Dykes.
Mixed zone of Micaceous and Carbonate-rich Kimberlite.
Carbonate-rich Kimberlite.
Micaceous Kimberlite.
Western-fragmental Kimberlite.
Eastern-fragmental Kimberlite.
Blue-black Kimberlite.
Blue-grey Kimberlite.
Intermediate Kimberlite.
Normal Kimberlite.
Normal Kimberlite with numerous quartzite inclusions.
Waterberg Quartzite.
Felsite.
Surface Rim.
Surface Rim of the Pipe.
Tunnels
Mains
No 1 Sub' Vertical Shaft.
No 1 Blue Shaft.
A
B
+12,000.
-98,000.
+11,000.
-99,000.
+13,000.
35°
0 3 6 9 12 15 13 21 24 27 30 33 36 39 42 45
42 32 24 21 14 7 0


PREMIER TVL. DIAMOND
MINING CO. LTD.
843' LEVEL
50' 0' 100' 200' 300'
SCALE 1:1000.
LEGEND.
Replaced Kimberlite Dykes.
Mixed zone of Micaceous and Carbonate-rich Kimberlite.
Carbonate-rich Kimberlite.
Micaceous Kimberlite.
Western-fragmental Kimberlite.
Eastern-fragmental Kimberlite.
Blue-black Kimberlite.
Blue-grey Kimberlite.
Intermediate Kimberlite.
Normal Kimberlite.
Normal Kimberlite with numerous quartzite inclusions.
Waterberg Quartzite.
Felsite.
- Tunnels -
- Mains -
No 1 Sub. Vertical Shaft
No 1 Blue Shaft
Surface rim of the pipe.
+12000
-98000
+11000
+13000
-99000

PREMIER TVL. DIAMOND MINING CO. LTD.
890' LEVEL.
50 0 100 200 300
SCALE 1:1000.
Surface Rim.
Surface Rim.
-Tunnels-
0 3 6 9 12 15 18 21 24 27 30 33 36 39 42 45
42
32
24
18
14
7
0
-Mains-
B
No 1 Sub Vertical Shaft.
No 1 Blue Shaft.
+12,000.
+11,000.
-98,000.
-99,000.
+12,000.
+13,000.
N
LEGEND
Replaced Kimberlite Dykes.
Mixed zone of Micaceous and Carbonate-rich Kimberlite.
Carbonate-rich Kimberlite.
Micaceous Kimberlite.
Western-fragmental Kimberlite.
Eastern-fragmental Kimberlite.
Blue-black Kimberlite.
Blue-grey Kimberlite.
Intermediate Kimberlite.
Normal Kimberlite.
Normal Kimberlite with numerous quartzite inclusions.
Waterberg Quartzite.
Felsite.
18.1.45.

PREMIER TVL. DIAMOND MINING CO. LTD.
1060' LEVEL.
50' 0 100' 200' 300
SCALE 1:1000
+12,000
-98,000
+11,000
-99,000
+12,000
-13,000
N
C
D
A
B
Tunnels
0 3 6 9 12 15 18 21 24 27 30 33 36 39 42 45
Mains.
42
32
24
18
14
0
No 1 Sub Vertical Shaft
No 1 Blue Shaft
To No 1 Shaft
North Blue Haulage
South Blue Haulage
Surface rim of the pipe
LEGEND.
Replaced Kimberlite Dykes.
Mixed zone of Micaceous and Carbonate-rich Kimberlite.
Carbonate-rich Kimberlite.
Micaceous Kimberlite.
Western-fragmental Kimberlite.
Eastern-fragmental Kimberlite.
Blue-black Kimberlite.
Blue-grey Kimberlite.
Intermediate Kimberlite.
Normal Kimberlite.
Normal Kimberlite with numerous quartzite inclusions.
Waterberg Quartzite.
Felsite.
18.1.49.