

# **THE GEOLOGY OF THE VAAL REEFS GOLD MINE,**

WESTERN TRANSVAAL

BY

**ROGER E. JACOB**

B.Sc. (Hons.)

DISSERTATION SUBMITTED FOR THE DEGREE OF MASTER OF SCIENCE  
AT RHODES UNIVERSITY, GRAHAMSTOWN.

•  
DECEMBER, 1966.

# **THE GEOLOGY OF THE VAAL REEFS GOLD MINE,**

WESTERN TRANSVAAL

BY

**ROGER E. JACOB**

B.Sc. (Hons.)

DISSERTATION SUBMITTED FOR THE DEGREE OF MASTER OF SCIENCE  
AT RHODES UNIVERSITY, GRAHAMSTOWN.

DECEMBER, 1966.

#### ABSTRACT

Rocks forming part of the Main-Bird Series and the Kimberley-Elsburg Series of the Upper Division of the Witwatersrand System are found in the mine.

The sequence studied starts with the Middle or MB 6 Zone of the Livingstone Stage followed by the Upper or MB 5 Zone.

The Vaal Reef, forming the base of the Vaal Stage, rests disconformably on the older rocks. The Stage is subdivided into the Vaal Reef Zone, the Lower Vaal Zone, the Argillaceous Zone and the Upper Vaal Zone. The lower and upper contacts of the Argillaceous Zone are gradational.

The Kimberley Stage follows unconformably and comprises the basal Gold Estates Conglomerate Zone, the Denny's Zone and the Gold Estates Zone.

The overlying Elsburg Stage may be subdivided into the Bastard Zone and the Upper Elsburg Zone on lithological grounds.

Most of the rocks are indurated quartz wackes with only a few orthoquartzite horizons such as the Denny's Zone and the immediate hangingwall of the Vaal Reef. Microscopically the rocks consist of detrital quartz and chert grains in a fine-grained sericitic to partly siliceous matrix which may constitute more than 50 per cent of the rock. Heavy minerals, such as zircon, chromite, rutile, leucoxene, pyrite, tourmaline, epidote, apatite and magnetite, occur in most of the zones.

The Vaal Reef, the economic horizon, is a small-pebble, oligomictic conglomerate, often containing thucholite seams and granules, and varying in thickness from a mere parting to more than five feet. There appears to be a correlation between greater pebble size and higher ore grade but no correlation of sorting coefficients and gold value.

The mineralogy of the Vaal Reef was studied by means of polished sections and heavy mineral concentrates. The minerals identified include gold, pyrite of several ages, pyrrhotite, chalcopyrite, uraninite, galena, brannerite, gersdorffite or cobaltite, skutterudite, linnacite, danaito, niccolite, pentlandite,

magnetite, zircon, chromite, rutile, leucocene, monazite, sphalerite, tourmaline, and fluorite.

From a study of the silver content of gold in the Vaal Reef it is concluded that the variations in apparent fineness are a reflection of the composition of the gold in the original source rocks.

There is a definite uranium-gold relationship in the Vaal Reef. With increase in grade the amount of  $U_3O_8$  increases but the  $U_3O_8$ : Au ratio decreases. Use of these ratios may indicate the payability in cases of incomplete core recovery.

The intrusive rocks were studied in detail. Six types of intrusive were found. From oldest to youngest these are quartz diabase ( of three varieties), amygdaloidal diabase, ilmenite mela-microdiorite, mottled microdiorite, olivine lamprophyre and ankeritic beforite, ranging in age from Lower Ventersdorp to post-Karoo. Most of the intrusives are highly altered due to the effects of regional metamorphism and deuteric alteration.

Later formations, such as the Langgeleven and Allanridge Formations of the Ventersdorp System and the Black Reef and Dolomite Series of the Transvaal System, occur on the property.

The various formations have been subjected to faulting and folding.

CONTENTS

	<u>PAGE</u>
INTRODUCTION . . . . .	1
<u>CHAPTER I</u> <u>THE WITWATERSRAND SYSTEM</u> . . . . .	4
<u>Stratigraphy.</u> . . . . .	4
Main-Bird Series . . . . .	4
Kimberley-Elsburg Series . . . . .	8
<u>Petrography</u> . . . . .	11
Main-Bird Series . . . . .	11
Kimborley-Elsburg Series . . . . .	19
Discussion . . . . .	22
Classification . . . . .	27
Heavy Mineral Distribution. . . . .	28
<u>CHAPTER II</u> <u>THE ECONOMIC GEOLOGY OF THE VAAL REEF.</u>	36
The Conglomerate . . . . .	36
The Ore Minerals . . . . .	40
The Heavy Minerals . . . . .	53
The Silver Content of Gold in the Vaal Reef. . . . .	54
The Uranium-Gold relationship in the Vaal Reef. . . . .	58
<u>CHAPTER III</u> <u>THE INTRUSIVE ROCKS</u> . . . . .	61
General . . . . .	61
Description of the intrusive rocks. .	65
Quartz Diabase. . . . .	65
Amygdaloidal diabase. . . . .	72
Ilmenite Mela-microdiorite. . . . .	75
Mottled microdiorite. . . . .	78
Carbonatite . . . . .	80
Olivine Lamprophyre. . . . .	90
The Alteration of the Intrusives. . .	93
Age Relationships. . . . .	95
<u>CHAPTER IV</u> <u>THE VENTERSDORP SYSTEM</u> . . . . .	97
Langgeleven Formation . . . . .	97
Allanridge Formation . . . . .	99
<u>CHAPTER V</u> <u>THE TRANSVAAL SYSTEM</u> . . . . .	101
Black Reef Series . . . . .	101
Dolomite Series . . . . .	102
<u>CHAPTER VI</u> <u>THE STRUCTURE OF THE VAAL REEF'S MINE</u> .	104
Unconformities and disconformities. .	104
Folding . . . . .	105
Faulting . . . . .	105
Structural history . . . . .	107
<u>CONCLUSIONS</u> . . . . .	109
<u>ACKNOWLEDGEMENTS</u> . . . . .	110a
<u>LIST OF REFERENCES.</u> . . . . .	111

## INTRODUCTION

### Situation:

This thesis deals with the geology of the Vaal Reefs Mine which is one of six large gold mines situated in the Western Transvaal about 100 miles southwest of Johannesburg. All these mines exploit the auriferous Vaal Reef. The mining area, known as the Klerksdorp Goldfield, is bounded to the south by the Vaal River, which serves as the provincial boundary. There are three towns serving the Goldfield. Klerksdorp is the oldest of these and the largest. Orkney and Stilfontein have developed purely as mining towns.

The mining area is rather flat at a more or less constant elevation of 4300 feet above sea level. The climate is hot and dry in summer with moderate winters and an average rainfall of 25 inches. Vegetation is grassland with occasional clumps of trees and shrubs.

### Circumstances

The author was employed as a geologist on the above mine for a year and a half and during this time became interested in the petrographic aspects of the intrusives and the sedimentary rocks. The stratigraphy had been worked out some time before but there was very little information regarding petrology and mineralogy. Accordingly, this aspect was investigated. The laboratory work was done during a six-month stay at Rhodes University while the remainder of the thesis was completed on a part-time basis.

### Mining History

Gold was discovered in the Klerksdorp area as long ago as 1887. According to Cartwright (1962), between this time and the outbreak of the First World War, there were over a hundred gold mines in which capital had been sunk. However it was not until 1933 that Anglo American Corporation formed the Western Reefs Exploration and Development Company. It was decided to establish a mine in 1936. In order to prospect fully the area to the east of the Western Reefs mine the Vaal Reefs Exploration and Mining Company was formed, administered by Anglo American Corporation. The results of drilling gave reasonable grounds for believing that the area in question was underlain by Vaal Reef of payable grade.

Initial development was undertaken from the joint Western Reefs-Vaal Reefs No.3 Shaft. In 1954 Vaal Reefs mine was

brought under separate management. In addition to the joint shaft there are at present two other shafts and a fourth is planned. Up to the end of 1965 over 13 million tons of ore valued at R155 million had been milled.

#### General Geology and Previous Work

The first systematic work on the geology of the Klerksdorp area was undertaken by L.T.Nel and as a result of his work a two-sheet map on a 1:60,000 scale of the Klerksdorp-Ventersdorp area was published in 1935 (Nel, 1935). In 1939 the Geological Survey Sheet No.61 and Explanation, dealing with the Country around Potchefstroom and Klerksdorp (Nel, 1939) were published, this work having been started by Nel in 1933.

In 1936 Beetz published a paper based on the diamond-drilling completed by the Western Reefs Exploration and Development Company (Beetz, 1936).

Baincs (1949) discussed certain aspects of correlation in the Klerksdorp and Orange Free State Goldfield areas and Simpson (1952) reported the results of radiometric logging.

It was only through papers by Collender (1960) and Strydom (1959) that a clear picture of the stratigraphy emerged. The latest work, of a very general nature, has been published by Wilson and others (1964).

From the above it is clear that virtually no mineralogical or petrological work has been done until the present.

The geological setting of the goldfield can be seen in the accompanying map (Fig.1.). The mines are found along the northwestern edge of the Witwatersrand basin, in the "Vaal Reef Basin" (Wilson and others, 1964) which is almost a separate entity due to structural effects (Brock and Pretorius, 1964). A great variety of rock types is represented in the area, from Old Granite through Dominion Reef System and Witwatersrand System to Karroo System, which blankets the southern portion of the map.

There are very few outcrops of the Upper Division of the Witwatersrand System rocks but to the north and northwest of the mining area the Lower Witwatersrand sediments are fairly well exposed as inliers in later Ventersdorp System rocks. The goldfield is situated almost entirely beneath the

Dolomite Series of the Transvaal System.

Fig.2 shows the position of the Vaal Reefs mine relative to the other mines in the Goldfield and also shows the location of boreholes and shafts.

CHAPTER 1

THE WITWATERSRAND SYSTEM

A. STRATIGRAPHY.

General

The rocks described below fall into the Main-Bird and Kimberley-Elsburg Series of the Upper Division of the Witwatersrand System. The stratigraphic column is pictured in Fig.3. This column has been in general use since 1959 when Strydom and Collender presented it at the geological Congress at Potchefstroom (Strydom, 1959; Collender, 1960).

Unfortunately, the nomenclature is not consistent and a certain amount of confusion has arisen, e.g. Collender's Bird Stage is Strydom's Vaal Reef Group and this in turn is the Vaal Reef Stage of Wilson and others. The general scheme followed is Time Stratigraphic, i.e. System, Series, Stage, Zone. Alongside the stratigraphic column (Fig.3) has been placed the lithostratigraphic classification of these rocks as they would appear in the scheme formulated by the American Commission on Stratigraphic Nomenclature (1961). In this latter scheme the Formation is the fundamental unit of rock stratigraphic classification and is defined as ". . . a body of rock characterized by lithologic homogeneity".

Because of very limited borehole information and paucity of underground exposures the rocks underlying the Middle Quartzites (MB6) of the Livingstone Stage are not described here but have been reported on by the previously mentioned authors.

The author has not included a sedimentological study of the Vaal Reef for two reasons, (a) it is felt that such a study would constitute a thesis on its own, and (b) the author was transferred from the mine before such a study could be undertaken.

THE MAIN-BIRD SERIES

Livingstone Stage

Middle (MB6) Zone:

Collender (1960) describes these rocks as 300 feet of mixed-pebble conglomerates in a dull grey quartzite. They are medium to coarse-grained, grey quartz wackes and quartz arenites (see under Classification), the

former invariably having a speckled appearance. A characteristic feature of the Zone is the presence of loose or scattered pebbles and lenticular conglomerate bands. The conglomerates are usually loosely packed and are composed of a variety of medium-sized pebbles (about 1 inch) and their thickness varies from 1 inch to several feet. As the conglomerates are lenticular they cannot be correlated over any distance.

Upper (MB5) Zone:

This is probably the most frequently encountered horizon in the mine as it forms the immediate footwall of the Vaal Reef. Cross-cuts to reef and footwall haulages are usually developed in this Zone, its thickness varying between 90 and 180 feet in Vaal Reefs (Fig.4). The variation in thickness is due to a disconformity below the Vaal Reef.

The base of the MB5 Zone is a thin, well mineralized, small-pebble conglomerate which suboutcrops against the Vaal Reef on Stilfontein, Zandpan and Western Reefs mines (Collender, 1960). The conglomerate carries sporadic gold and uranium values. It is overlain by several feet of grey to white, very siliceous, cross-bedded orthoquartzite. This siliceous quartzite attains a thickness of 15 feet to the east of No.2 Shaft. The oligonictic conglomerate overlain by a siliceous "bar" fulfils Sharpe's requirements for payable conglomerates (Sharpe, 1949) and the base of the MB5 should prove payable in certain parts of the Klerksdorp Goldfield.

The orthoquartzite is followed upwards by a uniform zone of quartz wackes. Over much of Vaal Reefs the contact between the orthoquartzite and the quartz wacke is occupied by a quartz vein which may be over 1 foot thick and which contains minerals such as galena, pyrite, ankerite and pyrophyllite.

The typical quartz wacke is a medium to coarse-grained, dirty-grey to khaki-coloured rock. Over most of the mine the Zone is uniform and homogeneous but to the east of No.2 Shaft there begins an alternation of clean, rather siliceous quartz wacke and dull, dirty, typical MB5 wacke. The alternation is due to varying current strengths during

deposition with a certain amount of reworking of the wacke resulting in the cleaner bands.

The rocks differ from the MB6 Zone in that scattered pebbles and pebble bands are absent except for a few thin, loose-pebble conglomerates in the No.2 Shaft area. For practical purposes dip and strike in the MB5 Zone are taken to be the same as in the Vaal Reef although the disconformity is of the order of half a degree. Locally however, i.e. in the 51-50 18 area, the disconformity reaches  $12^{\circ}$ .

### Vaal Stage

#### Vaal Reef Zone

The Vaal Reef occupies the base of the Zone which extends upwards for about 15 feet and consists of an orthoquartzite and conglomerate bands. The top of the Zone is taken to be the top of the Twelve Foot Marker conglomerate.

The Vaal Reef (Pls I and II) is the economic horizon and has different characteristics in different parts of the mine. Over most of the explored portion it is a small-pebble, oligomictic conglomerate varying between 1 inch and 8 inches in thickness with a thucholite seam at the base but in the No. 2 Shaft area it is very much thicker, widths of three to five feet being common.

Immediately overlying this reef is a very siliceous orthoquartzite or "bar" which is pale grey to white and is often coarse-grained with coarse speckling. This clean quartzite is a product of greater reworking of the sediment resulting in a washing-out of the clay and silt fractions. Known as the "grey glassy" quartzite on Vaal Reefs, it contains well-mineralized, gritty, small-pebble conglomerate lenses called "pyritic grits" which retain a constant position locally but have proved to be unreliable markers. They vary in thickness from 2 inches to 4 feet although they are usually less than 12 inches in thickness.

Both trough and tangential cross-bedding have been observed in the orthoquartzite. Towards the top of the "grey glassy" less glassy phases are occasionally developed. The thickness of the orthoquartzite varies (Fig.5) but averages 12 feet. It is overlain by the "Twelve Foot Marker".

This "Twelve Foot Marker" is a medium-pebble,



Plate I

Handspecimen of Vaal Reef with a thick thucholite seam, showing columnar structure, at the base. Note scarcity of pebbles. xl.7.

polymictic conglomerate with a fairly high proportion of quartz and quartzite pebbles. The conglomerate is well packed and is a consistent marker band. The thickness of this conglomerate varies from less than 1 foot to over 8 feet (Fig. 6.). It carries occasional gold and uranium values but is nowhere a profitable gold carrier.

#### Lower Vaal Zone

This zone consists essentially of medium and coarse-grained quartz wackes of very variable appearance from dirty, speckled, to clean, siliceous and occasional conglomerate bands. They may be confused with the MB5 and MB6 wackes although the speckling is less pronounced than in the MB6 Zone.

Conglomerate bands occurring within roughly 120 feet of the Vaal Reef form more or less reliable markers. They generally have a more siliceous matrix than MB6 conglomerates and are polymictic in character with quartz, several varieties of quartzite, silicified shale, chert and altered porphyry being the types commonly observed. The recognised marker bands are listed below:

The "Thirty Foot Marker" varies between 20 and 40 feet above the Vaal Reef and is a small-pebble, rather narrow conglomerates. The "Sixty Foot Marker" (60 feet  $\pm$  20 feet above the Vaal Reef) is a zone of medium-pebble, polymictic conglomerate extending over 5 to 10 feet, the individual conglomerate bands being separated by quartz wacke partings. The conglomerates are similar to the "Twelve Foot Marker" but tend to have a lower proportion of quartz pebbles.

About 30 feet above this is the "Ninety Foot Marker" (90 feet  $\pm$  20 feet above the Vaal Reef) which is not as well developed as the "Sixty Foot Marker" and is again a zone of conglomerates and intercalated wackes. The uppermost conglomerate is the "One hundred and twenty Foot Marker" which is not as well developed as the latter two markers, and which has been but rarely encountered. This is also a zone of medium-pebble, polymictic conglomerates with intercalated quartz wacke partings.

Small, scattered quartz and chert pebbles are often encountered and pyrite stringers are commonly developed. The quartz wackes grade into the Argillaceous Zone through a transition zone of interbedded very-fine and medium-grained



Plate II

Handspecimen, Vaal Reef. Small-pebble, oligomictic conglomerate consisting essentially of quartz pebbles in a siliceous matrix. Tiny specks of pyrite, surrounding the pebbles, are visible. Half natural size.

sediments. The position of the top of the Lower Vaal Zone is arbitrarily defined.

#### Argillaceous Zone

This horizon is a most useful marker and it is the equivalent of the Kimberley Shale in the Central and East Rand.

Here the rock has been described as a quartzitic shale (Strydom, 1959) or shaly quartzite (Collender, 1960) but it is, in fact, an argillite. Ripple marking is often developed in these rocks. The Zone grades into arenaceous quartz wackes upwards and downwards. The thickness reaches a maximum of 350 feet in the southeast but decreases to 300 feet towards the west and north.

#### Upper Vaal Zone

This zone increases in thickness from zero in the western portion of the mine to 150 feet in the southeast. The rocks are quartz wackes, often containing a high percentage of matrix. They show a great resemblance to the MB5 wackes but speckling is less pronounced and no conglomerates are present. The base of this horizon is arbitrarily defined and is usually taken to be the top of the first shale band (Collender, 1960). These rocks are overlain unconformably by the Gold Estates Conglomerate and the rocks near the contact are weathered, soft and friable.

### THE KIMBERLEY-ELSBURG SERIES

The Series is rather different in character from the underlying Main-Bird Series and is made up by the Kimberley Stage and the overlying Elsburg Stage.

#### Kimberley Stage

The Kimberley Stage comprises three Zones:

- Gold Estates Zone,
- Denny's Zone,
- Gold Estates Conglomerate Zone.

The Stage rests unconformably on rocks of the Main-Bird Series cutting these out in a northwesterly direction.

Gold Estates Conglomerate Zone

These rocks are most distinctive

The formation is composed of well to loosely-packed, large-  
pebble conglomerates, often many feet thick, alternating  
with dirty, khaki-coloured, medium to coarse-grained  
sandstone. The maximum thickness measured is in borehole  
M7 where it is 290 feet.

The top of the Zone has been reworked resulting in a  
reef known as the Denny's Reef where thickness varies from  
a few inches to 5 feet. It is characterized by smaller  
pebbles, oligomictic character and well-mineralized,  
siliceous matrix. Very patchy gold and uranium values have  
been obtained from this reef.

#### Denny's Zone

The Zone is named after G.A.Denny, the author of  
a book on the Klerksdorp Goldfield written in 1897 (Denny,  
1897). The maximum thickness of this Zone on Vaal Reefs is  
170 feet. The rocks are very light-coloured, often white,  
cross-bedded orthoquartzites, rather uniform in character.

Very pale yellow speckling may be present. In the  
northern part of the mine there is a dirty, gritty phase  
developed near the centre of the quartzites while southwards  
two such phases are found. These dirty phases may contain  
poorly-developed, small-pebble, polymictic conglomerates.  
The thickness of the gritty bands may reach 40 feet.

#### Gold Estates Zone

The change from the Denny's Zone to the  
overlying rocks takes place over a few millimetres. The  
rocks of this Zone are quartz wackes with thin bands of grey  
orthoquartzite. They are similar to the MB5 sandstones except  
that they tend to be slightly finer in grain and have more  
of a siliceous or "glassy" appearance. The rocks contain  
green, black and yellow speckling. The maximum thickness of  
this Zone in the mine is 950 feet.

As mentioned above the Zone contains several fine to  
medium-grained bands of grey orthoquartzites. The number  
and stratigraphic position of these "glassy" bands varies  
over the mine. Boreholes V3, M2 and M8 contain siliceous  
bands within 80 feet of the top of the Denny's Zone. A set  
of siliceous bands in about 100 feet of quartz wacke is present  
at an average of 180 feet above the top of the Denny's

quartzite. The base of this set is found between 120 and 300 feet above the top of the Denny's Zone. Yet another set of "glassy" bands occurs between 350 and 500 feet above the top of the Denny's quartzite and above this set a 15 foot thick siliceous band is often found at the top of the Stage, just below the Bastard Reef.

#### Elsburg Stage

There are few intersections of this Stage in the mine so that most of the information is derived from boreholes. It is best developed in M7 where the thickness is 1050 feet. The rocks approach quartzose sandstones in composition with quartz wackes being common and are very gritty and coarse-grained, containing scattered pebbles throughout. The Elsburg Reefs, mined on Western Reefs mine are no longer developed in the east.

The Elsburg Stage may be sub-divided as follows;

Upper Elsburg Zone,

Bastard Zone.

The Bastard Reef is found at the base of the Bastard Zone (about 500 feet thick) and is present as a zone of conglomerates, usually 15 feet thick. They are medium-pebble (pebbles 1 inch and less), polymictic rocks which are not well mineralized.

Upwards the Zone consists of coarse-grained sandstones with few scattered pebbles and these rocks grade into the Upper Elsburg Zone which consists of coarse-grained, gritty sandstones with scattered pebbles, these occasionally developing into loosely-packed, medium-pebble, polymictic conglomerates. Towards the top the sandstones acquire a creamy-yellow colour.

B. PETROGRAPHYTHE MAIN-BIRD SERIESLivingstone Stage

Middle (MB6) Zone: In hand specimen the rocks are medium to coarse-grained, gray, indurated sandstones which usually have a speckled appearance, the speckling being due to black chert grains, green phyllosilicates, milky quartz grains, and yellow rutile and leucoxene. Scattered pebbles and conglomerates are found throughout the Zone. The pebbles consist of a variety of types of quartz, quartzite, silicified shale, chert, porphyry and silicified, altered igneous material.

Microscopically the rocks consist of detrital quartz and chert grains in a very fine-grained sericitic matrix. The chert grains tend to be well rounded but tend in certain cases to merge into the matrix. According to Pettijohn (1957) chert is less stable than quartz and is liable to interstratal solution. The presence of chert is a good indication that at least part of the sediment has been derived from a previous sediment.

Detrital flakes of muscovite were observed in most of the thin sections studied. These are usually bent and display strain extinction.

The matrix is sericitic in character although in the cleaner wackes a fair amount of quartz is present. The sericite shreds and flakes are very fine-grained and masses of shreds often reveal a rectangular pattern. The distribution of the sericite is not entirely uniform, some parts of the matrix containing more quartz. Blebs of sericitic material with rounded form are interpreted as being alteration products of original feldspar (Fuller, 1958).

Chlorite is usually present in the matrix and may be fairly common making up to 6 per cent of the whole rock. It occurs as fairly large aggregates, sometimes with a spherulitic structure, and also as tiny individual flakes together with the sericite. The varieties prochlorite and penninite have been identified, the former being more abundant.

Calcite is often developed in the matrix. This mineral is later than other minerals and replaces them, and in fact this is the only horizon, with the exception of the Argillaceous Zone, which regularly contains calcite.

Chloritoid is also commonly developed in these rocks.

It has the form of euhedral, lath-shaped, prismatic crystals of maximum length between 0.19 and 0.34 mm. The crystals occur singly or as small, loose clusters. Twinning is extremely common in the chloritoid crystals.

Upper (MB5) Zone: The base of the MB5 is a small-pebble, oligomictic conglomerate which is rarely more than 6 inches thick. The pebbles are mostly quartz and quartzite together with porphyry, chert, and silicified shale. In certain areas of the mine, e.g. 62 Level and in the 55 South 27 area the conglomerate shows a very strong resemblance to the Vaal Reef and is overlain by lenticular, small-pebble conglomerates known as "pyritic grits".

Quartz grains in the matrix of the conglomerate show considerable interpenetration, strain effects being more pronounced at points of grain contact. The matrix is sericitic with a fair amount of pinnite being present occasionally enclosing authigenic rutile needles. Some of the chlorite is thought to be an alteration product of original pyroxene or amphibole.

Pyrite is by far the most abundant opaque mineral present. It has the same modes of occurrence as in the Vaal Reef (see later section on opaque minerals), viz. rounded, possibly detrital grains; later overgrowths on these grains; "porous" or concretinary grains and late-formed irregular blobs and veinlets. Galena may replace pyrite and is also found with chalcopyrite, which is present as irregular inclusions in pyrite. Rutile, derived from nearby leucoxene, has attacked and replaced pyrite along crystallographic directions. Leucoxene is very common as rounded, irregular masses and short, remobilized veinlets. Chromite is found as rounded grains and these are often cracked.

The siliceous bar overlying the base of the MB5 is an orthoquartzite or pressolved quartzite (see later under Classification). The rock is medium-grained and well-sorted and is made up of more than 95 per cent quartz and chert. About 4 per cent sericitic matrix is present. (Pl. III). Interpenetration effects are marked, this being mainly due to pressure solution at points of grain contact. Secondary growth of quartz on detrital quartz grains is plainly visible in ordinary light. Chlorite is very rare in the rock.

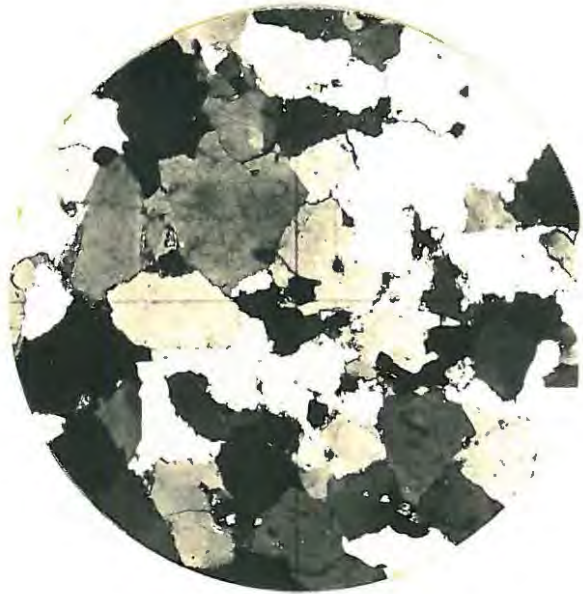


Plate III Orthoquartzite, MB 5 Zone. Virtually no sericitic matrix. Note suturing of grain contacts. Crossed nicols, x 32.

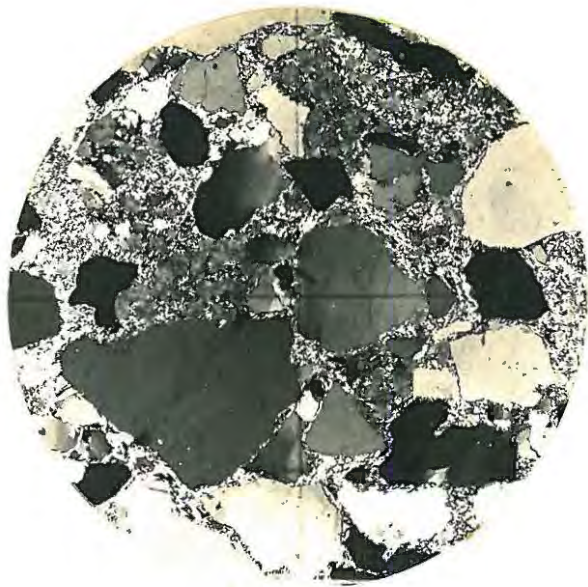


Plate IV Quartz wacke, MB 5 Zone. Poorly sorted, subangular and subrounded quartz grains in a sericitic matrix. Crossed nicols, x 32.

Overlying the orthoquartzite is the typical MB5 quartz wacke. In hand specimen the rock is a medium to coarse-grained, dull, grey to khaki-coloured, indurated sandstone with a slightly speckled appearance.

Microscopically the rock consists of quartz grains, usually rather angular, set in a fine-grained sericitic matrix containing variable amounts of quartz (Pl. IV). Beside quartz, other detrital, sand-sized grains are composed of chert, fine-grained quartzite, sericitized feldspar and possibly altered porphyry.

The matrix is sericitic and is present in amounts up to 42 per cent. The mode of occurrence of the sericite is similar to that in the MB6 Zone. Together with the sericite is found an abundance of rutile, either as single crystals or as clusters of tiny needles. Chlorite is present in every thin section examined. It occurs as individual flakes in the matrix and as larger aggregates, giving rise to the speckling seen in hand specimen. Often two varieties of chlorite are present in the same thin section, prochlorite being more abundant than penninite.

Chloritoid was found in less than one quarter of the thin sections studied. It has very much the same mode of occurrence in these rocks as it has in the MB6. The length of the prismatic crystals averages 0.2 mm.

Shale partings are common in the MB5 rocks. Microscopically these partings consist of angular quartz grains surrounded by a wealth of sericitic material. The sericitic material makes up more than 80 per cent of the rock. Chlorite, muscovite and rutile are plentiful while chloritoid may be present in small amount.

The quartz wackes show greater variability in the No.2 Shaft area where dull-grey wackes alternate with clean quartz wackes which approach quartzose sandstones or quartz arenites in composition. These arenitic rocks are pale-coloured often with a very pale-yellowish tinge. Immediately underlying the Vaal Reef in this area is a siliceous bar very similar to the immediate hangingwall of the Vaal Reef. The rocks do not display a great deal of interesting sedimentary features but graded-bedding has been observed in the 2/54 37 area.

Vaal Stage

Vaal Reef Zone: The Vaal Reef is a small-pebble, oligomictic, well-mineralized conglomerate which varies from a mere parting to a reef 5 feet thick (including intercalated quartzite partings). A thucholite (carbon) seam is often developed at the base (Pl. I). The reef is composed of pebbles resistant to attrition. The pebbles are quartz, quartzite and chert, the chert invariably being less rounded and of lower sphericity than the quartz and quartzite pebbles. Quartz pebbles are the most abundant rudaceous constituents present. Young (1917) has stated that most of the quartz pebbles in the reefs are vein quartz, which assumes a great variety of structures and often the quartz has recrystallized to a schistose aggregate. A large number of quartz pebbles are single crystals and all are invariably strained and filled with abundant tiny inclusions.

Quartzite pebbles consist of medium and fine-grained types. Chert pebbles are very fine-grained and are occasionally pyritized. Slight variations in grain size give the pebbles a banded appearance. Porphyry pebbles, which occur rarely, are similar to those found in the MB6 conglomerates.

In order to ascertain whether there is a systematic variation in the relative amounts of the above types pebble-counts were carried out on samples from the whole mine (Fig. 7 and Table 1). The percentage of quartz varies between 85 and 92 per cent, that of chert between 4 and 9 per cent and that of quartzite between 3 and 7 per cent. Chert percentages can be very useful in determining palaeocurrent slopes as the amount of chert increases relative to quartzite away from the source (Schlee, 1957). In order to minimize the effect of size on pebble-type, pebbles were counted in two size-classes, the 8-16 mm and 16-32 mm classes (Table 1). As few pebbles of chert were observed in the 16-32 mm class percentages were more variable than in the smaller class. No significant change in the chert percentage over the mine was determined probably because too small an area was involved.

TABLE 1

The relative proportions of quartz (Q), quartzite (Qe) and Chert (C) pebbles in the Vaal Reef.

Area	No. of rdgs	Number %			Combined %		
		8-16 mm	16-32 mm		Q	Qe	C
A	2	89	4	7	89	4	7
		95	2.5	2.5			
B	2	87	7	6	87	7	6
		87	7	6			
C	2	91	4	5	92.5	3	4.5
		96	0	4			
D	4	85	6.5	8.5	85	6.5	8.5
		88	4	8			
E	2	86.5	4.5	9	87	5	8
		94	4	2			
I	4	88	4.5	7.5	88.5	5	6.5
		90	10	0			
J	3	87.5	4.5	8	86	5	9
		73	15	12			
K	3	88.3	3	8.7	88.4	3.1	8.5
		92	5	3			
N	2	87.6	4.8	7.6	89	5	6
		92	6	2			
O	6	88.2	4.6	7.3	88	5.3	6.7
		85.5	10.5	4			
Q	5	84.5	6	9.5	85	6	9
		86	7	7			

Average %

87.8

5.0

7.2

The material filling the interstices among the pebbles consists of detrital quartz and chert grains surrounded by authigenic minerals. The quartz grains show pressure solution effects when in contact. While sericitic material may

constitute 77 per cent of the matrix, quartz is very common, reaching 45 per cent. Chlorite can make up 70 per cent of the minus 2 mm. fraction of the reef and in this case the reef has a black-coloured matrix in hand specimen with the chlorite usually being mistaken for thucholite. Where the chlorite is abundant it has replaced the matrix and also many quartz grains (Pl.V): in ordinary light the original outlines of the quartz grains can be clearly seen. The varieties of chlorite in the Vaal Reef are prochlorite and penninite.

Chloritoid was not often encountered in the Vaal Reef but is common in certain samples. From its form it must have been one of the first minerals to crystallize.

The rocks immediately overlying the Vaal Reef are somewhat variable from medium-fine-grained to coarse-grained and cross-bedded. The rock-type is an orthoquartzite or pressolved quartzite with quartz and chert grains constituting over 95 per cent of the rock, the balance being made up of sericite shreds, chlorite and chloritoid. In the 52 20 area the orthoquartzite is dead-white in colour, a feature directly attributable to igneous activity in the area. A thin section of this rock shows it to be a true quartzite, considerable suturing of the grain contacts having taken place as a result of recrystallization.

The typical orthoquartzite is slightly speckled by chlorite aggregates and contains many pyrite stringers. Secondary growth of silica on quartz grains is as common as in the MB5 orthoquartzite.

Isopachs of this "grey glassy" (Fig. 5.) show a dome and basin effect and in a general way the thicker "grey glassy" overlies higher-grade Vaal Reef but there is no close relationship between individual payshoots and thickness of the orthoquartzite. The orthoquartzite is thinner at No.2 Shaft, its thickness rarely being greater than six feet here. The overlying Marker in this case is a small-pebble, polymictic conglomerate but it is not certain that the "12 Foot Marker" and this conglomerate are one and the same band.

The "12 Foot Marker" overlies the orthoquartzite and this is a reliable marker band in the Nos. 1 and 3 Shaft areas. Its thickness varies as shown in the isopach map in Fig. 6. The isopachs show a thicker zone running north-northeast and

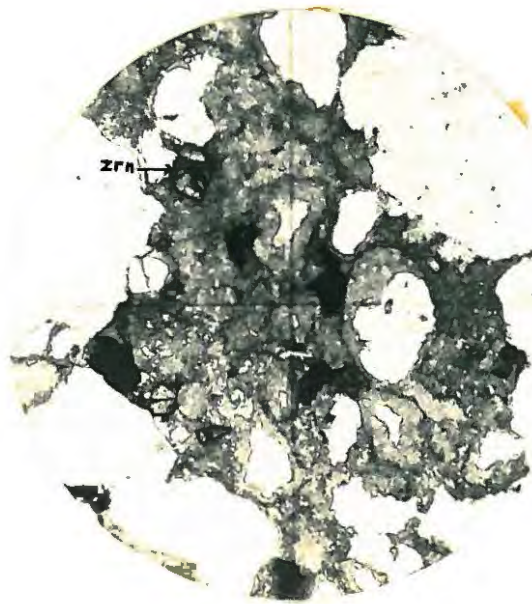


Plate V Quartz grains (white) in the Vaal Reef partially and completely replaced by chlorite (grey). The matrix has been completely replaced. Pyrite (black) and a zircon grain (zrn) are unaffected. Polarized light, x 37.

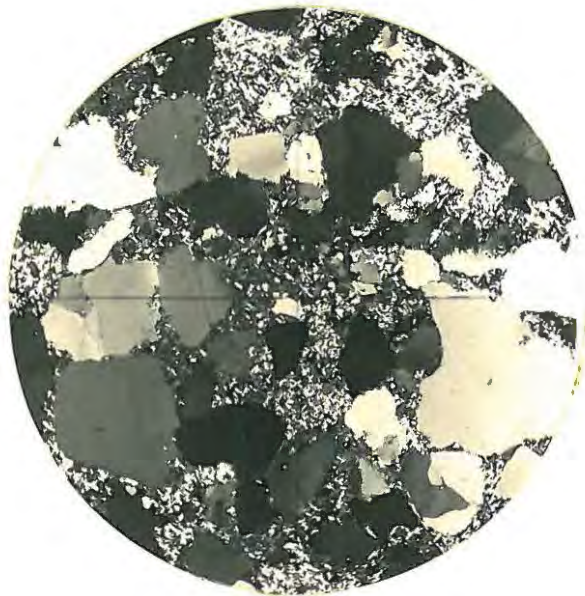


Plate VI Quartz wacke, Lower Vaal Zone. More or less equant quartz grains set in a sericitic matrix which has attacked grain edges. Crossed nicols. x 32.

this coincides with isopachs of thinner "grey glassy". Thus it appears that the thicker conglomerate was deposited where the orthoquartzite had been slightly eroded. The trend of the thicker marker is parallel to that of the payshoots. The conglomerate consists of well-rounded pebbles with a fairly siliceous matrix which is identical to the overlying quartz wacke.

#### Lower Vaal Zone:

The rocks are quartz wackes often similar to the MB5 and MB6 rocks and consist of quartz grains together with minor amounts of chert fine-grained quartzite, porphyry, schist and probable altered feldspar grains in a sericitic matrix (Pl.VI). The rocks often have a glassy appearance caused either by coarse grain size or matrix rich in silica.

The matrix is sericitic in character with silica usually being present and may occasionally contain more quartz than sericite. The sericite often forms thin envelopes around quartz grains and has partly replaced them along their edges. Rutile needles are common in the matrix, either singly or in clusters.

Chlorite is common in these rocks being found as the varieties prochlorite and penninite. Small amounts of biotite partially or completely altered to chlorite are also present. Muscovite grains are occasionally partly replaced by chlorite.

An interesting fact is that chloritoid was encountered in every thin section examined. It occurs as euhedral, prismatic crystals of high relief, often twinned, of average length between 0.2 and 0.3 mm.

#### Argillaceous Zone:

In hand specimen the rock is very fine-grained but appears to be slightly coarser grained than a shale. It is grey in colour and usually has a green tint. Furthermore very fine yellow and black speckling may be present. The author has not observed graded bedding in these rocks. Pyrite is commonly present, sometimes in fairly large concentration.

Microscopically the rock is composed of quartz grains surrounded by fine-grained phyllosilicates. The largest

quartz grains are 0.8 mm. across but such large grains are scattered. For the most part the quartz grains are elongated and irregular in outline (Pl. VII). The angular effect is enhanced by partial replacement by the phyllosilicates.

Chlorite is present in large amount. Penninite is more abundant than the second variety, prochlorite, which seems to have formed from the alteration of biotite. The amount of chlorite plus quartz is greater than the amount of sericite.

Sericite is found as shreds and as concentrations which may be after original feldspar. Coarser grained muscovite is invariably present (Pl. VII). Chloritoid is rarely present and has the same mode of occurrence as in other horizons.

Calcite is always present as small rhombs and as irregularly-shaped grains but is never a major constituent. Rutile needles were not found to be as common as expected.

The formation is well-bedded but is not very fissile. A common feature is the presence of faulting and mylonite along bedding planes. Ripple-marking is fairly well preserved in these rocks. The ripple-marks are usually symmetrical and very rarely have wavelengths greater than 2 inches.

Because of the incipient metamorphism and the non-fissile character of the rock the author suggests that the term argillite is more appropriate than the term argillaceous quartzite which is in common use.

#### Upper Vaal Zone:

In hand specimen the rock is very similar to the MB5 quartz wackes except that muscovite is more abundant. The rocks are medium-grained, have a dirty appearance and are grey in colour.

The matrix is usually abundant in amount and is sericitic in character with minor amounts of quartz. Because of the large amount of matrix, pressure solution between grains in contact is reduced to a minimum, the quartz grains appearing to "float" in the sericitic material.

Prochlorite is a common constituent of the matrix together with small amounts of penninite. Chloritoid was not observed.



Plate VII Argillite, Argillaceous Zone. Tiny quartz grains surrounded by very fine-grained phyllosilicates. Some muscovite flakes are visible. Crossed nicols, x 32.



Plate VIII Orthoquartzite, Denny's Zone, showing interpenetrating quartz and chert (ch) grains. Sericitic matrix absent. Crossed nicols, x 32.

THE KIMBERLEY-ELSBURG SERIESKimberley StageGold Estates Conglomerate Zone:

These rocks are unmistakable in hand specimen consisting as they do of large pebbles and cobbles up to greater than 8 inches in size set in a sandy matrix rich in sericite.

The conglomerates are polymictic in character, a great variety of pebble types being present. Types observed by the author are milky, clear, smoky and opalescent blue quartz; green, whitish, dark grey and fine-grained grey quartzites; red jasper, banded and massive chert, silicified shale of assorted colours and altered porphyry. Collender (1960) states that boulders of the Vaal Reef have been extracted from the Gold Estates in the Ellaton Gold Mine, indicating that the Main-Bird Series had consolidated prior to the deposition of the Kimberley-Elsburg Series.

The Denny's Reef is a potential gold-carrier. It consists of quartz, quartzite and chert pebbles with minor amounts of silicified shale, porphyry etc. set in a dark matrix. Penninite is a very common constituent of the matrix and replaces other earlier minerals. For the most part the matrix is siliceous, sericite being less common than in the underlying conglomerates.

The ore minerals in the Denny's Reef are as follows: pyrite, as rounded grains, cubed cubes, porous concretions and irregular veinlets; chromite as rounded, often cracked grains; leucocene as rounded grains and irregular masses and thucholite, haematite, chalcopyrite and pyrrhotite in very small amount.

Denny's Zone :

This rock type is rather similar to the quartzite overlying the Vaal Reef and that overlying the base of the MB5. A difference is that the Denny's quartzite is paler in colour, often being of a dead-white hue. The rock is well-sorted and rather fine-grained. The quartz grains are closely-packed with a very small amount of matrix in the form of scattered concentrations of sericite (Pl. VIII). Secondary growth of silica on quartz grains is well displayed.

The original grain outlines are marked by lines of tiny inclusions. Muscovite flakes are not common nor are chlorite aggregates.

Gold Estates Zone:

These rocks are again similar to the MB5 quartz wackes. However, they are slightly finer grained and somewhat more glassy in appearance. The rocks occasionally have a green tint. They are normally speckled in black (chert), dark green (chlorite) and yellow (rutile and leucoxene). Wilson and others (1964) mention red speckling (jasper) but the author has not observed this to date. Essentially the rocks are medium and coarse-grained sandstones with quartz grains set in a more or less sericitic matrix (Pl.IX).

The detrital grains show somewhat more variety than the underlying beds with grains of quartz, fine-grained quartzite, chert, feldspar, altered porphyry, unidentifiable igneous material and also rutile-rich shale. The quartz grains contain abundant inclusions which often exhibit parallelism. Secondary growths of silica on quartz grains are not common. Mortar structure as a result of pressure solution is likewise not common.

The matrix is normally sericitic with occasional more siliceous patches. Where the matrix is highly sericitic tiny grains of quartz can still be seen. Chlorite was present in every thin section examined and it occurs as individual flakes in the matrix and as larger aggregates giving rise to the dark green speckling. No chloritoid was encountered in these rocks and this may be a useful fact in distinguishing Main-Bird rocks from those of the Kimberley-Elsburg Series.

As described in the above section dealing with the stratigraphy of these rocks, bands of grey to dark grey orthoquartzite occur within the succession of this Zone. These rocks are fine-grained and contain about 10 per cent matrix, consisting of sericite, chlorite and silica. Secondary growth of silica is more pronounced and pressure solution along grain contacts is very common.

Two mechanical analyses were carried out in the rocks of this Zone, one on typical quartz wacke and the other on

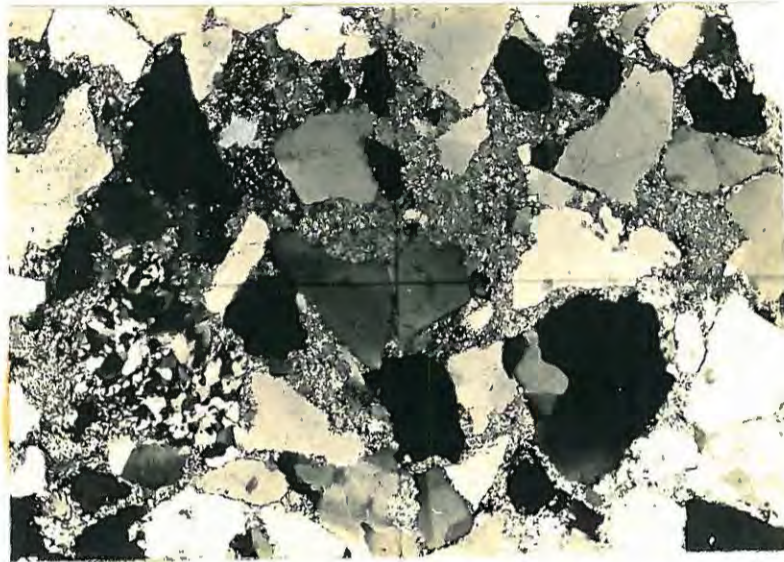


Plate IX Quartz wacke, Gold Estates Zone. Quartz grains and a fine-grained quartzite particle, partially replaced along grain edges by the sericitic matrix. Darker patch (sil) is more siliceous. Crossed nicols, x 32.



Plate X: Vaal Reef. Secondary uraninite (grey) replacing pyrite (white) and surrounding gold (au). Below this chalcopyrite replaces uraninite. Gold also coats a rounded pyrite grain and partially fills a fracture in another pyrite grain. Polished section, x 94.

an orthoquartzite band. Due to the indurated nature of these rocks the analyses had to be performed on thin sections and the resulting cumulative curves were later corrected following a method suggested by Packham (1955). The corrected and uncorrected curves are shown in Fig. 8. The table below lists the various statistical measures and it can immediately be seen that the orthoquartzite is finer grained.

Table 2

Showing 1st quartiles, 3rd quartiles, Trask Sorting coefficients and median sizes of Gold Estates quartz wacke and orthoquartzite.

	Q1	Q3	$\frac{Q1}{Q3}$	Median
quartz wacke	0.69	0.34	1.43	0.48mm
orthoquartzite	0.35	0.15	1.52	0.23mm

Elsburg Stage

This stage is noticeably coarser grained than any of the other stages and tends to have a cleaner or more siliceous appearance than other rocks.

The rocks commonly contain a variety of pebble types among which are clear, milky, smoky, pink and opalescent blue quartz; fine-grained yellowish grey and dark grey quartzite, black, yellow and green shale; yellowish-grey, grey, black and banded grey chert; red jasper; altered yellow and grey porphyry; tuff and several unidentifiable altered igneous rocks, possibly schists and lavas.

Most of the sand-sized detrital grains are quartz, together with small amounts of chert, altered feldspar, altered porphyry, quartzite and shale.

Because of the lesser amount of matrix relative to other rocks, pressure solution is more widespread, more grains being in contact. Secondary growth of silica on quartz grains has not taken place to a large extent.

The matrix is sericitic in character. Quartzose patches are scattered about, generally close to areas where a fair amount of pressure solution has taken place. Chloritoid was not observed in any thin sections. Chlorite is present in

minor amounts as single grains and as aggregates. It partially replaces muscovite flakes. Some of the muscovite appears to be authigenic. There is no microscopic difference between the rocks of the Bastard and Upper Elsburg Zones.

#### DISCUSSION

Most of the rocks examined are inherently similar and often it is difficult to assign a specimen to any particular formation. The similarity is borne out by a microscopic study.

#### Composition

Generally the rocks are composed of detrital quartz grains set in a sericitic to partly siliceous matrix. Other detrital grains are of minor importance, e.g. chert, fine-grained quartzite, altered feldspar, altered porphyry, shale, muscovite, biotite and unidentifiable igneous material.

Sericite is the dominant matrix mineral, occurring as tiny shreds and flakes. Other minerals include chlorite as penninite and prochlorite, quartz, rutile as fine needles and various heavy minerals, described in another section. Chloritoid is present in the Main-Bird Series, although rare in the MB5 rocks, while it is absent from the Kimberley-Elsburg Series. Calcite was found as a regular constituent only in the MB6 Zone and in the Argillaceous Zone.

A table of compositions as given by Dollar Stage counts is shown below (Table 3). The category of "matrix quartz" is only approximate as it is almost impossible to decide which is detrital quartz in the silt-size and which is matrix material. All quartz less than very-fine sand-size has been assigned to this category. The sericite category includes all the muscovite present in the rocks, the latter being present in only small amount. Any very similar mineral such as pyrophyllite or talc has been included in the sericite column. Microscopic methods did not allow of the identification of pyrophyllite. Its presence in the Upper Witwatersrand System has been recorded by Fuller (1958).

Table 3

Composition of Upper Witwatersrand System rocks from the Vaal Reefs mine.

Horizon	Quartz %	Rock fragms %	Matrix quartz %	Sericite %	Chlorite %	Other %
Elsburg Stage	64-84	1-5	2-9	9-21	1-3	Trace
G.E. Zone	55-82	1-17	2-6	9-32	1-5	Tr.-2
Denny's Zone	87-97	0-2	0-2	1-6	0-2	Tr.
U.V. Zone	~ 29	~ 1	~ 10	~ 52	~ 8	Tr.
Argill. Zone	38-46	0-1	see Qtz	14-23	27-36	3-9
L.V. Zone	52-67	2-5	6-15	15-32	3-12	0-2
V.R. Zone } "grey glassy" }	~ 95	0-1	see Qtz	2-5	0-3	Tr.
MB5 Zone	45-72	0-9	2-15	10-40	0-6	Tr.-3
MB5 orthoqtz	~ 96	0-1	see Qtz	~ 4	Tr.	Tr.
MB6 Zone	57-73	1-12	4-15	5-35	1-6	Tr.-6

### Texture

#### Grain Size:

For the purpose of grain size measurements the Wentworth Scale was used (Pettijohn, 1957). The average grain sizes of the quartz grains in the rocks were determined from thin sections and these are reproduced in the table below:

Table 4

Average grain sizes of Main-Bird and Kimberley-Elsburg rocks, expressed in millimetres.

Zone	Av. Gr. size, mm.
Bastard	0.75
G.E.	0.49
Denny's	0.33
U.Vaal	0.45
Argill.	0.09
L.Vaal	0.55
MB5	0.69
MB6	0.70

No major regular trends in grain size can be postulated as the Argillaceous Zone and the Denny's Zone are finer grained than other rocks. However it can be seen in hand

specimen that the Elsburg Stage is coarser than the other Stages and so the Upper Witwatersrand System does become coarser grained upwards.

The rocks of the MB6 Zone are usually coarse to medium-grained as are the MB5, Lower Vaal, Vaal Reef Zone and Upper Vaal rocks. The Denny's quartzite is medium to fine-grained, the Gold Estates Zone is medium-grained, the grey, siliceous bands being fine-grained and the Elsburg rocks are coarse to very coarse-grained.

Shape of grains:

A study was carried out of the average sphericity of the sand-sized detrital grains in each horizon. This was done by means of a comparison of randomly selected grains in thin section with sphericity charts in Krumbein and Sloss (1963). Steyn (1963) found that the sphericities measured in this fashion by him differed from computed values only in the second decimal place.

Seeing that a comparative study was made no correction was made for the bias introduced by thin section measurement. The true sphericity will be lower than the figures given. Twenty grains were selected in each of 60 thin sections. The average sphericities are shown in Table 5.

Table 5

Average sphericities of quartz grains in Main-Bird and Kimberley-Elsburg rocks.

Zone	Sphericity
Bastard	0.64
G.E.	0.63
Denny's	0.62
U.Vaal	0.56
Argill.	0.53
L. Vaal.	0.61
MB5	0.57
MB6	0.59

Not reliable

The interesting point is that each of the Series has a more or less constant sphericity, the figure for the Kimberley-Elsburg Series being greater than that for the Main-Bird Series. The probable reason is that many of the grains from

the lower Series have become incorporated into the overlying Series with some modification during transport.

Grain roundness measurements were attempted in the MB6 but it is felt that the results will be misleading as the grains have suffered a certain amount of attack by the matrix. Generally the grains are angular and subangular.

Grain orientation:

The orientation of grains in any particular direction is not pronounced in these rocks. Thin sections were cut of two oriented specimens of Gold Estates wacke. The sections were cut in the bedding plane and both of these showed reasonably well marked maxima with good agreement. The direction of elongation of the grains is roughly at right angles to the trend of payshoots in the Vaal Reef. However there is doubt as to whether a preferred orientation of grains is due to primary deposition conditions or to later tectonic phenomena. Fuller (1958) believes that the preferred orientation in the rocks he studied is caused by tectonic effects.

Features of quartz grains

The features of 50 quartz grains in each of 60 thin sections were observed and are reported below.

1. Single crystals and aggregates: The majority of quartz grains are single crystals, the remainder being aggregates or twins. Table 6 lists the percentage of single crystals in the sediments studied.

Table 6

Percentage single crystals in quartz grains in rocks of the Main-Bird and Kimberley-Elsburg Series.

Zone	% single crystals
U. Elsburg } Bastard }	79
G.E.	76
Denny's	90
U. Vaal	80
Argill.	90
L. Vaal	80
MB5	79
MB6	75

From the above there do not appear to be any noticeable trends in the proportion of single crystals. The reason for the greater percentage of single crystals in the Denny's and argillite is given by Conolly (1965). He states that the percentage of polycrystalline quartz in a sediment varies with change in the modal size of the detrital grains. Generally fine-grained sandstones will have lower percentages of polycrystalline quartz.

2. Strain effects:

Of the grains examined all aggregates or twins showed strain extinction. The percentage of single crystals which showed strain extinction is tabulated below.

Table 7

The percentage of single crystals with strain extinction in Main-Bird and Kimberley-Elsburg rocks.

Zone	% strained single crystals
U. Elsburg } Bastard }	61
G.E.	86
Denny's	90
U. Vaal	79
Argill.	91
L. Vaal	91
MB5	84
MB6	67

The figures vary considerably. Conolly (1965) states that the amount of undulatory quartz in a sandstone is affected by post-depositional effects, primarily due to folding and faulting and secondarily to the effects of diagenesis.

There is no evidence of any trend in the above figures.

3. Inclusions:

Inclusions in quartz grains such as fine rutile needles, heavy mineral grains such as zircon etc. were not commonly observed. Very tiny inclusions, either liquid or crystals, often arranged in parallel lines, are very abundant in most of the detrital grains. The author was unable to identify these inclusions with the equipment at his disposal. Secondary overgrowths and recrystallized quartz

tend to be free of inclusions but lines of fine inclusions demarcate original grain boundaries so that the presence of secondary overgrowths of silica on quartz grains can be easily confirmed.

#### CLASSIFICATION

The rocks of the Upper Witwatersrand System are for the most part incorrectly termed "quartzites", e.g. the Glossary of Geology and Related Sciences defines a quartzite as a "granulose metamorphic rock consisting essentially of quartz". As can be seen from Table 3 the amount of quartz varies between 30 and 97 per cent. The rocks are in fact indurated sandstones.

The majority of the rocks described contain only small amounts of rock fragments and very little feldspar; hence they cannot be classed as greywackes (Moorhouse, 1959; Pettijohn, 1957) even though the percentage of matrix reaches more than 50 per cent. The term sub-greywacke as defined by Pettijohn (1957) is likewise not applicable. As the amount of feldspar is very low the designations arkose and/or feldspathic quartzites cannot be applied.

The amount of matrix is generally greater than 20 per cent or very close to this figure. Hence the rocks fall into the quartz wacke class of Krumbein and Sloss (1963). In Williams and others' classification (1958) quartz wackes can contain anything from 10 per cent matrix upwards.

Rocks which contain more than 90 per cent quartz are termed quartz arenites or orthoquartzites. The various siliceous bars and the Denny's quartzite fit these requirements. Due to their indurated appearance the term orthoquartzite is preferred. Skolnick (1965) has proposed the term "pressolved quartzite" for rocks with the megascopic characteristics of quartzite but which have formed by pressure solution of grains, i.e. those that have undergone non-metamorphic changes. This term could be used for the above quartz-rich rocks.

The rocks of the Elsburg Stage contain less sericitic matrix than most of the other sediments but could still be called quartz wackes in the classification of Williams, Turner and Gilbert (1958). They do not readily fall into the classification of Krumbein and Sloss (1963). Quartzose

sandstones appear to be the closest term applicable.

The Argillaceous Zone consists of an indurated, fine-grained rock which is more massive than a shale. The matrix constituents have recrystallized to low degrees of regional metamorphism. Before recrystallization the rock was probably a coarse-grained mudstone or siltstone. The most appropriate name for this rock-type is argillite (Williams and others, 1958; Krumbein and Sloss, 1963).

#### THE HEAVY MINERAL DISTRIBUTION

A quantitative heavy mineral study of seven samples from several Zones in the stratigraphic column was undertaken with a view to establishing the nature and proportions of the minerals present.

The study was carried out on concentrates yielded by crushing and subsequent separation in bromoform. The results are expressed as weight percentages as number frequencies could not be obtained due to fracturing of heavy mineral grains during crushing.

#### Method.

The method is described in some detail so as to guide any future investigation. Approximately 400 grams of rock were found to be more than sufficient for an analysis.

The rock was broken down to chips which were then weighed. These chips were then crushed to pass through a 60 mesh sieve at which stage the heavy minerals are mostly free of adhering quartz grains. The crushed rock was weighed and the loss through crushing determined. This was found to be less than one per cent. As the amount of crushed rock was too large for separation in bromoform it was carefully panned three times over using a large porcelain evaporating basin and a somewhat larger container as a receptacle for the panned-off material. Loss from panning was negligible.

During drying the panned concentrate acquired a coating of rust caused by iron flakes and chips derived from the mortar used for crushing. These were removed by passing a strong bar-magnet over the concentrate and placing the material removed in cold, dilute (1:5) HCl. The iron dissolved but any magnetite present remained unaffected. The insoluble material was returned to the concentrate which then had to be treated to remove the coating of iron oxide that

tended to mask minerals and also perhaps add to their weight.

The concentrate was treated in a way recommended by Drosdoff and Truog (1935) whereby the oxide coating is removed by treatment with  $H_2S$  and 0.05N HCl. This method does not affect HCl-soluble minerals such as apatite.

After drying, the concentrate was separated in bromoform, several funnels being used. Koen (1955) and Wardaugh (1960) have pointed out the dangers of too-rapid separation and addition of excess material at any one time.

Inspection of the resulting concentrate under a binocular microscope showed an abundance of pyrite which masked most other minerals and for the purpose of counting it became necessary to remove this pyrite. A portion of the concentrate was kept aside for reference and identification purposes.

The methods attempted for removal of the pyrite were treatment with warm, 15 per cent  $HNO_3$ , and cold 50 per cent  $H_2O_2$  (Milner, 1962). The latter method required careful control, proved to be very slow and was thus abandoned.

The reaction between pyrite and 15 per cent  $HNO_3$  resulted in a grey-green, insoluble deposit being left on pyrite grains, hindering further reaction. This was thought to be a form of sulphur but was insoluble in  $CS_2$ . Whiteside (1944) has mentioned similar difficulties. The deposit was light but could not be decanted as it surrounded other heavy mineral grains. Prolonged treatment with 15 per cent  $HNO_3$  eventually removed the deposit. It is not known what the substance was.

Dissolution of the pyrite left quartz in the concentrate which had previously been attached to the pyrite grains. A further separation in bromoform was thus necessary.

Further separation by means of an electromagnet was attempted but this met with very limited success as several important minerals, viz. zircon, rutile and leucocoxene have very low magnetic susceptibility (Krumbein and Pettijohn, 1938; Twenhofel and Tyler, 1941) and could not be separated by this means.

As stated above, number percentages would give spurious results. In order to facilitate weight percentage calculations the heavy mineral concentrate was sieved into three fractions: + 100 mesh, + 200 mesh and - 200 mesh. Each of these fractions was weighed.

That portion of the concentrate kept aside before nitric acid treatment and the above three fractions were then studied and all minerals present were identified. After identification each of the fractions was mixed, quartered and mounted for counting.

Several methods of mounting were attempted. Sanders and Kravitz (1964) suggest a method of mounting that allows examination both by reflected and transmitted light. Mounting media used by the author were methyl methacrylate, Canada balsam, Araldite (epoxy resin), Aerolite (epoxy resin) and NHP mounting plastic. Plates used were silicone-treated glass, Vaseline-treated glass and Teflon. All these products were experimented with as the materials recommended by the above two authors were unobtainable. None of the combinations was entirely successful although the NHP mounting plastic and Vaseline treated Teflon gave the best results. The mounts were not permanent and peeled off the glass slides after a few weeks. The method proved to be very time consuming and could be avoided in certain cases by counting grains on a white-surfaced stage using a good binocular microscope with very intense reflected light. In this case the grains were mounted in Canada balsam on glass slides.

Dryden (1931) has suggested that 300 grains should be counted in order to obtain reasonable accuracy. An average of 630 grains was counted in each mount. Counting was carried out with the aid of a mechanical stage following the method of ribbon sampling advocated by van der Plas (1962) whereby no bias, due to the size of the grains, is introduced. The entire mount was traversed since Koen (1955) has emphasized the dangers of covering only part of a mount in a heavy mineral count. From the number frequencies in each size class weight percentages were calculated.

#### The Heavy Minerals:

Chlorite: As the specific gravity of this mineral is very close to that of bromoform it could not be determined quantitatively. That portion of it which sank in bromoform was counted and its weight later deducted during calculation.

Zircon: A large variety of zircon grains was observed. The colour ranges from very pale pink, almost colourless to a deep reddish-purple while the shapes vary greatly from elongated, prismatic or stout, prismatic or almost spherical

to irregular. The prismatic grains generally show a certain degree of rounding although a few are almost angular. The well rounded, almost spherical grains are not very common and probably represent recycled zircon from earlier sediments.

Zoned zircon grains were found in all concentrates. Other varieties include twinned grains and grains filled with tiny inclusions. The surfaces of the grains are normally smooth but fine frosting was also observed.

The zircon grains are smaller than other grains but are usually slightly larger than the chromite grains. Most of them occur in the -200 mesh fraction, allowing for the fact that many grains were fractured. Zircon grains are normally smaller in the quartz wackes than in the Vaal Reef, a feature which is to be expected. The proportion of zircon to other minerals varied in the different size fractions, e.g. leucoxene is more abundant than zircon in the coarser size fractions but is less abundant in the finest fraction.

Chromite: This mineral is not common in the quartzites but is widespread. Most of the grains are well-rounded, some being perfectly spherical, while partly rounded octahedra with flat faces still visible are less common. They occur almost invariably in the -200 mesh fraction and have a dull, microscopically frosted surface.

Rutile: Rutile normally occurs as honey-coloured grains, either as slender rods or as stumpy, prismatic crystals. Much of the rutile is authigenic. It is also found as fine needles in chlorite grains giving them a pale, yellowish-green colour. Definitely detrital rutile, although found, is not common. Such grains are rounded, rather dark brown and often faintly striated.

Leucoxene: The colour of the rutile grains varies according to the amount of rutile in them. Viljoen (1963) states that X-ray analyses of the leucoxene he studied showed it to consist mainly of quartz and rutile. The variation in colour is from white to orange. Under a binocular microscope the mineral has a matte appearance and normally occurs as rather large, rounded grains. However a large amount of irregular, redistributed leucoxene is found.

Most of the leucoxene is found in the + 100 mesh fraction. Occasionally there is difficulty in deciding whether a particular grain is rutile or leucoxene. The

parent mineral of the leucoxene is no longer present but was probably ilmenite. Titanomagnetite may also have contributed to its formation. Some original structure can be recognized in polished sections.

Pyrite: Pyrite is by far the most common mineral in the concentrates. Other sulphides which occur together with the pyrite were dissolved in the nitric acid treatment and are grouped with pyrite for the purpose of weight-percentage calculations. A description of these can be found in the section on opaque minerals. Such sulphides are often common in the Vaal Reef but appear to be very uncommon in the arenaceous rocks.

Much of the pyrite is found as irregular grains, perfect cubes and pyritohedra together with a small amount of rounded grains, oval to spherical in shape with rather dull surfaces. These grains may be original detrital pyrite or pseudomorphs after an original oxide, e.g. magnetite.

Tourmaline: Tourmaline is common in certain concentrates. While some of it is detrital a certain amount is authigenic as seen by its habit. It is found as rounded grains and as long, slender prisms. Occasionally an authigenic overgrowth on a rounded grain was observed in thin section. The variety, confirmed by refractive index determinations, is schorlite. Many colours were observed, e.g. dark blue, pleochroic to light blue (sometimes so dark that the mineral appeared opaque), dark brown, pleochroic to pale yellow-brown, and dark green, pleochroic to green. On occasion, grains having different colours at either extremity were encountered.

Epidote: The presence of epidote was recorded in only the MB5 Zone. It occurs as pale green, transparent, clear, rounded, prismatic grains showing faint pleochroism. The mineral is of no quantitative importance.

Apatite: Apatite occurs only in the Argillaceous Zone where it occurs as colourless, well-rounded small grains concentrated in the -200 mesh fraction. Occasionally tiny inclusions are present in these grains.

Magnetite: Magnetite is of no quantitative importance. The grains are always very tiny and have a metallic lustre. The mineral is found as partly rounded octahedra and cubes both in the Vaal Reef and Argillaceous Zone.

Chloritoid: This authigenic mineral is a dark greenish-blue colour. It has fairly low birefringence and a flaky form. The grains often contain irregular inclusions.

Other ore minerals are not described here. Uraninite was largely altered to secondary uraninite and so was lost in the crushing and separation.

### Results

These are given in the accompanying tables. The results are expressed as weight percentages and thus are not directly comparable with other workers' results which have been stated in terms of number frequencies (Viljoen, 1963; Coetzee, 1962).

Table 8

The amount of heavy minerals (including pyrite) and the amount of pyrite in the heavy mineral concentrates expressed as weight percentages.

Zone	% heavy minerals	% pyrite
Bastard	0.36	83
G.E. (top)	0.22	77
G.E. (bottom)	0.22	89.5
U. Vaal	0.15	74
Argill.	0.02	33
L. Vaal	0.07	84
MB5	0.26	74.5

Table 9

The relative amounts of heavy minerals, excluding pyrite, expressed as weight percentages.

Table 9 continued . . . . .

ZONE	Chromite.	Tourmaline	Rutile	Zircon.	Leucorene.	Chloritoid	Apatite.	Magetite.
Bastard	8	-	46	15	31	-	-	-
G.E. (top)	2	6	42	10	40	-	-	-
G.E. (bottom)	9	3	40	19	29	-	-	-
U. Vaal	1	12	26	33	28	-	-	-
Argill.	-	3	41	9	see rutile	33	13	1
L. Vaal	-	10	-	8	15	67	-	-
MB5	1	10	42	30	17	-	-	-

Table 10

The amounts of heavy minerals, expressed as weights relative to 100 mg. of zircon (pyrite excluded). Koen (1955) recommends this method of presentation rather than that of percentages because the relative percentages of all minerals in the concentrate will alter even if only one mineral varies.

ZONE	Chromite.	Tourmaline.	Rutile	Zircon.	Leucorene.	Chloritoid.	Apatite.	Magetite.
Bastard	54	-	304	100	204	-	-	-
G.E. (top)	16	52	388	100	376	-	-	-
G.E. (bottom)	49	16	218	100	155	-	-	-
U. Vaal	1	36	79	100	86	-	-	-
Argill.	-	40	479	100	see %.	374	155	17
L. Vaal	-	112	-	100	185	812	-	-
MB 5	4	30	140	100	57	-	-	-

For the most part the heavy mineral assemblages are similar in all the horizons studied, some species being absent in certain horizons and present in others. Gold is absent from the concentrates.

Pyrite is by far the most abundant heavy mineral. The percentage of heavy minerals in the Vaal Reef (see under Economic Geology), including pyrite, reaches 9.8 per cent

while the figure for the arenaceous rocks varies between 0.02 per cent in the Argillaceous Zone to 0.36 per cent in the Bastard Zone. The average for the rocks is 0.22 per cent.

Zircon, rutile, leucoxene and pyrite are common to all horizons. Tourmaline is absent only from the sample from the Bastard Zone. Epidote is present only in the IB 5 sample and apatite only in that from the Argillaceous Zone.

Minerals like chloritoid, some of the tourmaline and also rutile are not detrital and are thus not of correlative value. Few of the detrital heavy minerals are of quantitative importance. These are zircon, chromite and leucoxene. Through the succession chromite decreases in amount downwards, zircon increases and leucoxene remains more or less constant. Compared with the Vaal Reef the quartz wackes contain relatively more leucoxene and less chromite.

From the results it appears that the source remained largely unchanged throughout deposition of these Witwatersrand System beds, with the possible exception of the Argillaceous Zone, which has a distinctive heavy mineral assemblage. The slight variations in heavy mineral species may aid in correlation of the rocks over limited areas although the variation in relative proportions would perhaps have greater importance with regard to such correlation.

The mineral species present are all stable and are representative of a variety of source-rock types as indicated in Table 4-11, Krumbein and Sloss (1963), viz.

- (a) Apatite, monazite (in the Vaal Reef) and zircon may be derived from acid igneous rocks,
- (b) chromite, leucoxene and rutile are derived from ultra-basic igneous rocks,
- (c) rounded zircon grains are derived from reworked sediments.

Several factors influence the heavy mineral composition of a rock, viz. weathering, abrasion, selective sorting and post-depositional solution (van Andel, 1959). Pettijohn (1957) states that the last is probably the most important factor. Thus, with the passage of time, the less stable minerals dissolve leaving only the most stable minerals.

Selective sorting is probably an important factor as the grain sizes of some heavy mineral species are very much

larger than those of other species so that the relative proportions may vary according to the median grain size of the sediment. It is not possible to determine the importance of weathering during transportation or selective mechanical destruction in the direction of transport but both of these factors must have contributed to the final assemblages. It is likely that their importance did not vary much throughout the depositional period. If the source of the minerals altered the mineral assemblage would have changed accordingly but this does not appear to be the case.

## CHAPTER 2

### THE ECONOMIC GEOLOGY OF THE VAAL REEF

#### 1. The conglomerate

In the Nos. 1 and 3 Shaft areas the Vaal Reef is a small-pebble, oligomictic conglomerate varying between 1 inch and 8 inches in width, often carrying a thucholite seam at the base. In low-grade areas the thucholite seam is usually absent and the conglomerate is more polymictic in character. In the No. 2 Shaft area the reef is still oligomictic but is very much thicker, widths of three to five feet being common, together with intercalated lenses of quartzite. This thick reef contains gold throughout although the greatest concentrations are along the lower contact. Thucholite seams may be present in the reef at No. 2 Shaft and up to three such seams have been observed in one thick band of reef. The thickness of the thucholite rarely exceeds one-tenth of an inch. As mentioned in the "Silver content of Gold" section it is possible that the differences in the reef in the No. 2 Shaft area from the remainder of the mine are related to the movement on the intervening Kromdraai fault.

At No. 2 Shaft and to a lesser extent elsewhere the Vaal Reef exhibits characteristics similar to those described by Antrobus (1956) for the Basal Reef in the President Steyn

Mine, i.e. the presence of two reefs, one slightly older than the other and partly eroded, with the erosion products being incorporated in the upper reef. The lower reef may be separated from the upper reef by up to six feet of siliceous quartzite, although the quartzite is rarely more than two feet thick (Fig.9). The lower reef is normally only a parting with scattered pebbles and granules of thucholite along it but gold and uranium values may be high. The quartzite between the two reefs is an orthoquartzite, very similar to the immediate hangingwall of the Vaal Reef. It does however have a purplish or violet tint and no pyritic grits are developed in it. These features correspond almost exactly with those described by Antrobus. He states that where one reef only is developed the gold value is greater as gold from the lower reef (now eroded) has become incorporated into the upper reef. The evidence from sampling on Vaal Reefs is inconclusive as the upper reef may or may not show enrichment in the vicinity of the suboutcrop of the lower reef.

The Vaal Reef is composed of pebbles resistant to attrition, these being quartz, quartzite and chert. The variation in the proportions of these constituents has already been discussed and it can further be observed that in higher-grade areas the chert percentage is constant at 8.5 per cent and greater than in low-grade areas where it averages 6 per cent. It appears that this relative increase of chert is due to greater reworking of the conglomerate and that the less resistant quartzite pebbles were abraded. The reef at No. 2 Shaft, however, does not follow the above pattern. Here the total chert percentage,  $6\frac{1}{2}$  per cent, is less in the high-grade areas than in the low-grade areas where it is 9 per cent. The reason for this is not clear.

Pebble-size measurements were carried out in order to ascertain whether gold content is a function of pebble size and sorting coefficient. At each of 79 localities the 10 largest pebbles in one square foot were measured (Table 11 and Fig.7.). The nature of the reef is such that measurements had to be performed in only two dimensions. The greatest visible diameter was measured in each case. No systematic variation in pebble size was evident when a moving average plan was drawn up. The author feels that a

greater number of pebbles per locality, perhaps over a larger area, should have been measured for a definite trend to show up. Nevertheless the average of the 10 largest pebbles in higher-grade areas (23.0 mm.) is greater than that in low-grade areas (21.7 mm.), leading to the conclusion that higher gold values are associated with greater pebble size. A similar correlation has been reported by Pirow (1920), Reincke (1927) and Steyn (1963). It must be stressed that the result is only empirical as no statistical analysis was applied to the data. A detailed study of pebble size variation appears promising.

Size analyses were performed on selected samples of Vaal Reef in order to compare median sizes and sorting coefficients in different parts of the reef. Only the thicker reef in the Nos. 1 and 3 Shaft areas and the reef in the No. 2 Shaft area were selected. Each sample was divided into four sections from base to top and the long and short axes of all pebbles over 4 mm. were measured. The mean diameter was calculated for each pebble, i.e.

$$\text{mean diameter} = \frac{\text{long axis} + \text{short axis}}{2}$$

Cumulative curves were then drawn and the various statistical measures read off (Fig. 10 and Table 12). Number frequencies were used and size classes were one to two millimetres apart. Steyn (1963) found that both number frequency curves and weight frequency curves gave similar results. The curves were not corrected for the bias of two dimensional measurement as they were used for comparative purposes only.

Table 11

Average maximum pebble size of the ten largest pebbles in one square foot. The letters A, B etc. refer to areas in which readings were taken (Fig.7).

Area	A	B	C	D	E	F	G	H
Average maxm. size mm.	22.4	22.7	22.6	25.4	21.0	19.3	18.8	22.3
No. of observations	7	6	6	6	1	1	8	3

Table 11 cont. . . .

Area	I	J	K	L	M	N	O	P	Q
Average maxm. size mm.	25.5	20.6	22.8	24.0	23.2	21.8	23.3	18.5	18.7
No. of observations	6	4	8	1	7	2	6	1	4

Table 12

Sorting coefficients (Trask value), 1st Quartiles,  
Third Quartiles and Median pebble sizes.

Sample No.	shaft area	sorting coeffic.	3rd quartile	1st quartile	median size mm.
551 a. top	3	1.51	10.5	4.4	6.6
b.		1.46	10.9	5.1	7.4
c.		1.28	8.5	5.2	6.3
d.		1.29	10.0	6.0	7.4
combined data		1.36	9.8	5.3	7.0
346 a. top	1	1.44	9.3	4.5	6.7
b.		1.33	9.0	5.1	6.6
c.		1.27	10.4	6.5	7.8
combined data		1.28	8.3	5.1	6.8
829 a. top	2	1.28	7.7	4.7	6.0
b.		1.38	9.8	5.2	7.4
c.		1.30	8.6	5.1	6.4
d.		1.46	10.0	4.7	6.4
combined data		1.35	8.8	4.8	6.5
831 a. top	2	1.21	7.2	4.9	5.8
b.		1.19	6.8	4.8	5.7
c.		1.24	7.2	4.7	6.1
d.		1.35	12.1	6.7	9.7
combined data		1.41	9.8	4.9	5.1
840 a. top	2	1.20	7.3	5.1	5.8
b.		1.37	9.6	5.1	6.8
c.		1.33	7.5	4.2	5.9
d.		1.36	8.5	4.6	6.3
combined data		1.30	8.2	4.8	6.2

The results show that the Vaal Reef from the Nos. 1 and 3 Shaft areas has a greater median pebble size than that from No. 2 Shaft. The interesting fact is that the median pebble size for the lowest portion of the reef is greater than the median for the entire reef and the median for the topmost portion is smaller than that for the other sections (Fig. 10). A glance at the assay sections shows that the base of the conglomerate is most strongly mineralized and the top most weakly mineralized. These facts fit the previous findings that greater pebble size is characteristic of higher grade reef. The Trask Sorting Coefficient was calculated in each case. According to this scale the sorting of the pebbles is very good in all cases. There is no systematic variation in the sorting coefficient upwards in the reef and the reef may be better sorted towards the top or base. It is interesting to note that the reef from the Nos. 1 and 3 Shafts is better sorted than that from No. 2 Shaft, and also that while the Nos. 1 and 3 Shaft samples are better sorted at the base, the samples from No. 2 Shaft are better sorted towards the top.

Figure 11 shows an inch-pennyweight plan of gold values in the Vaal Reef, modified from a plan drawn up by the Sampling Department at the mine. There is a very definite elongation of the payshoots in a north-south direction. When the centres of the shoots are joined, a braided pattern, much like that of streams on a deltaic plain, shows up. The current directions, not determined by the author, were probably from north to south (Antrobus, personal communication, Brock and Pretorius, 1964, Pl.6). Thus the payshoots represent areas of greater reworking by currents, probably stronger than in surrounding lower-grade areas where the average maximum pebble size is less.

## 2. The Ore Minerals

Detailed accounts of the ore minerals occurring in Witwatersrand System conglomerates have been given by several authors, notably Liebenberg (1955), Ramdohr (1958) and Viljoen (1963). While Liebenberg did study samples from the Vaal Reef neither Ramdohr nor Viljoen described the mineralogy

of that horizon. Several authors have described the mineralogy of similar gold-bearing conglomerates such as the Ventersdorp Contact Reef and the Black Reef. As far as the author is aware this is the first account of the ore minerals of the Vaal Reef.

The minerals present are similar to those found in other reefs and textures and relative ages differ only in detail. The minerals were identified from their optical properties, reflectivities and x-ray data.

#### Pyrite

Pyrite is by far the most abundant ore mineral present and one of the most interesting. It occurs in several forms with at least two generations being present. The forms are as follows: rounded grains, overgrowths, porous grains and irregular, late-formed bodies.

##### a. Rounded grains:

The amount of this type varies in different samples and either this or other forms may predominate. In a general way, the more highly pyritized the reef is, the higher the gold content.

These rounded grains do not enter into intergrowths with any other minerals. Their size varies considerably in polished section from less than 0.05 mm. to 1.0 mm. (Pls. X and XI). Many of the grains show traces of cubic cleavage which is well displayed in grains which have been trapped between large quartz grains or pebbles and have been crushed to some extent. Many of the grains have suffered a certain amount of attack by the matrix resulting in slight irregularities of grain boundaries. Much of the rounded pyrite is of a similar size to the detrital grains of zircon and chromite.

Fisher (1939) believed that a considerable amount of the rounded pyrite formed at the expense of quartz grains. This appears to be unlikely as the average grain size of the quartz is far greater than that of the rounded pyrite. Recently the idea has been mooted that most of the rounded pyrite grains may have been original detrital material (Ramdohr, 1958). Viljoen (1963) feels that this is the case in the Main Reef and Main Reef Leader, while Malan (1959) favours such an origin for the rounded pyrite in the Dominion Reef conglomerates.

The envelopment of these grains by younger pyrite is often very striking and is a common feature in the Vaal Reef. The rounded grains are separated from the overgrowths by hairline cracks so that the original grain boundaries can be recognised without difficulty. Polished sections of pyrite along cross-bedding foresets directly overlying the reef show many rounded pyrite grains along the cross-beds, almost invariably surrounded by later pyrite overgrowths.

Along the boundaries between the two types of pyrite, lenses of chalcopyrite, secondary uraninite and galena are found although not common. Rounded pyrite grains are occasionally observed in thucholite seams. These generally have pyrite growths surrounding them. Pyrrhotite, thucholite and gold are later than the rounded pyrite and may fill fractures in such grains. This pyrite is also older than authigenic rutile needles as these also fill fractures in the rounded grains.

Small, rounded inclusions of chalcopyrite and/or pyrrhotite and occasionally gold are a common feature in this type of pyrite. Ramdohr (1958) states that this ". . . shows the pyrite lumps are true pebbles".

b. Overgrowth pyrite: As previously stated, a large number of rounded grains are surrounded by later overgrowths which possess crystal- or irregular outlines (Pls X, XI, XII). Such overgrowths also surround zircon, chromite and leucoxene grains. Overgrowths of this nature are later than some of the porous pyrite (see under c.).

The enclosing pyrite is usually very similar in physical characteristics to the rounded pyrite grains and can be distinguished from them only by the presence of the above-mentioned cracks but this is not invariably the case as some is porous material. This type is earlier than thucholite which may replace it.

c. Porous pyrite: The porous pyrite corresponds to Ramdohr's "Concretionary pyrite". Grains of this type vary greatly in size and may or may not have a rounded appearance. The "pores" usually consist of quartz or matrix material. Often these pores exceed in proportion their host. Many occurrences show a greater proportion of pyrite in the centre gradually decreasing in amount outwards, while in other examples the pyrite shows fewer pores at the borders.



Plate XI Vaal Reef. Rounded pyrite grains and overgrowth pyrite (py), gersdorffite or cobaltite (ger), chromite (chr) and leucoxene (le). Secondary uraninite (u), in veinlet form, replaces pyrite. Polished section, x 92.



Plate XII Mineralized foreset, Vaal Reef. Rounded pyrite grains (py) and a porous pyrite grain (centre) surrounded by later overgrowth pyrite showing crystal outline. Polished section, x 92.

This pyrite has grown by replacement of the reef matrix which has been affected more easily than replacement of quartz grains so that almost complete quartz grains may be enclosed within pyrite. Several porous pyrite bodies give the impression that the pyrite has been partially replaced by the reef matrix but this is not the case as close inspection shows the tiny constituent pyrite particles to be bounded by crystal faces.

In certain parts of the mine pyrite occurs in the Vaal Reef as irregular patches and blebs which vary in size from 2 mm. to several centimetres, the remainder of the reef being apparently barren of ore minerals. Macroscopically the pyrite is massive. When polished the pyrite has well developed cubic zoning.

The blebs of pyrite have come into existence through replacement of pebbles and matrix and the zoning is caused by incomplete replacement by the pyrite. This has been controlled by the crystal structure. The pyrite encloses grains like zircon and chromite but does not replace them. A particularly striking feature is the effect of the zircon on the surrounding pyrite which is discussed later.

Porous pyrite grains may be enveloped by later overgrowths of pyrite similar to that surrounding rounded pyrite grains (Pl. XII). Other porous grains occur as pseudomorphs after minerals like limonite and rock fragments (Pl. XIII). Examples of these are very similar to some figured by Ramdohr (1958; Figs. 29, 30, 36).

Tiny grains of gold and chalcopyrite are occasionally seen in these porous structures and porous grains may be found in thucholite seams. This type of pyrite is younger than the rounded type but is older than the overgrowth type.

d. Irregular pyrite: This type includes veinlets and other pyrite which does not readily fall into any of the other groups. Predominant in some specimens but of minor importance in others, this type is always present.

A certain amount is found in quartzite pebbles and may well have been present in these pebbles at the time of deposition.

When in the form of veinlets, the pyrite is often associated with pyrrhotite which rims it and appears to be later. The pyrrhotite may have been formed by dissociation

of the pyrite under conditions of dynamic metamorphism.

This type is older than the thucholite and is also older than the gold, which replaces it. The relationship between the irregular pyrite and secondary uraninite was not determinable.

While some of the irregular pyrite may be derived from earlier pyrite, much has been introduced later, either by hydrothermal solutions or from dykes, which often contain a fair amount of sulphide mineralization.

#### Pyrrhotite

Pyrrhotite may be very common in some specimens but absent from others. It occurs as a late mineral filling cracks and replacing pyrite. It is common as irregular patches and as loosely-knit, lath-shaped aggregates, pyrite and galena occurring as tiny inclusions in them. Twinning was often observed in polished section.

Rarely, the mineral occurs as small, rounded inclusions in pyrite grains. Ramdohr (1958) states that this represents an older generation of pyrrhotite. In one specimen the pyrrhotite is rimmed by a light grey mineral which occurs as needle-like inclusions in pyrrhotite laths and along cracks. The mineral is of a light grey colour in ordinary light and is strongly anisotropic. It is present in only very small amount and could be valleriite or an alteration product, haematite.

One polished section of a highly pyritized portion of reef displayed a fan-shaped aggregate of stumpy laths of pyrrhotite containing thin lamellae of niccolite which is harder and strongly anisotropic, showing green polarization colours.

Pentlandite is rarely seen in association with pyrrhotite in the Vaal Reef. It was observed as probable exsolution intergrowths in subhedral grains of pyrrhotite. Pyrite is invariably present in such instances.

With regard to age the pyrrhotite appears to be later than both the overgrowth and irregular pyrite. Pyrrhotite also appears to be later than thucholite but there is a certain amount of doubt about this. The pyrrhotite appears to have occupied the space between thucholite granules in one

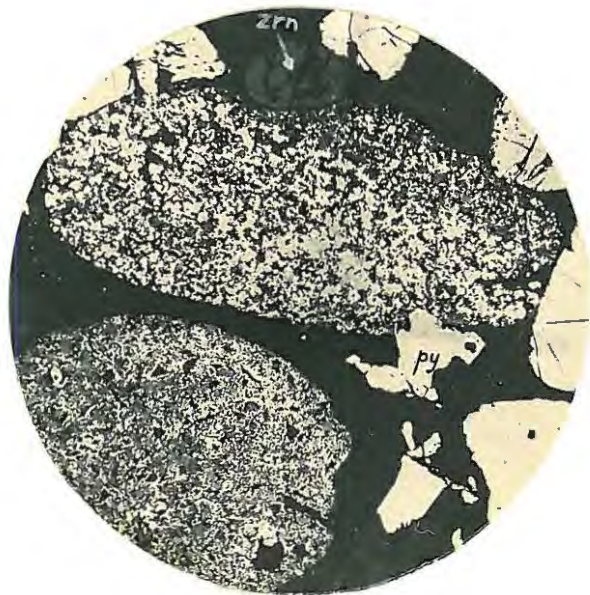


Plate XIII: Vaal Reef. Two rounded grains of porous pyrite, younger than the fractured zircon grain (zrn) and older than the irregular pyrite (py) which replaces one of the grains. Polished section, x 94.



Plate XIV: Vaal Reef. Pyrrhotite veinlet (po) has forced its way among contiguous thucholite granules which contain a multitude of uraninite grains (u) and radiogenic galena specks. Polished section, x 92.

less doubtful case (Pl. XIV). Pyrrhotite is later than secondary uraninite and together with chalcopyrite may partially replace "ghost" uraninite grains.

Nel (1958) states that the presence of pyrrhotite implies the action of metamorphism, generally thermal metamorphism due to intrusion. Much of the pyrrhotite has been derived from dykes as the concentration of pyrrhotite tends to increase in the vicinity of these intrusions.

#### Chalcopyrite.

Chalcopyrite is rare in the Vaal Reef. It has several modes of occurrence and is late in the paragenesis. It is often found as small, rounded or pear-shaped inclusions in pyrite grains. Another mode of occurrence is as anhedral grains in the reef matrix where it is normally associated with other sulphides.

Chalcopyrite and pyrrhotite generally occur together. While both minerals are late, the pyrrhotite appears to be younger and replaces the chalcopyrite along crystallographic directions. Viljoen (1963) has found that where chalcopyrite and pyrrhotite occur together in the Main Reef and Main Reef Leader, chalcopyrite appears to be younger.

He states that it was one of the last to crystallize.

Chalcopyrite encloses pyrite grains and is later than all pyrite. It may also be later than skutterudite but is older than gold in its present form.

#### Uraninite.

The mineral is usually recognised by its occurrence in thucholite. It very rarely occurs as well rounded grains. The grains are normally shattered to some extent (Pls. XIV, XV). Occasionally the fragments can be fitted together showing that separation is limited. Liebenberg (1955) states that the fracturing is due to metamorphism while Malan (1959) maintains that the shattering probably took place during deposition in the case of the Dominion Reef conglomerates.

The uraninite is light grey in polished section with a low reflectivity. Abundant tiny specks of galena are invariably associated with the uraninite. Faint, dark brown internal reflections can be seen. A close association of

gold and uraninite was not observed in all cases although sampling values show that this is usually the case.

The size of the uraninite grains varies up to a maximum of 0.1 mm. Where only tiny fragments of uraninite remain in thucholite the thucholite may be bordered by thin galena rims which are certainly derived from original uraninite, the galena having migrated to this position.

There is definite evidence of replacement of uraninite by thucholite. Liebenberg (1955) states that the final stage of replacement of uraninite by thucholite is a concentration of galena particles around previous rims of uraninite.

Often the thucholite appears to have acted as a protective covering for the uraninite, judging from the manner in which it is usually altered to secondary uraninite when not enclosed in thucholite.

The phenomenon of alteration or reconstitution of the uraninite to secondary uraninite is very common in the Vaal Reef. Liebenberg (1955) reports that 60 to 70 per cent of the uraninite is altered to some extent. The author has been unable to confirm the identity of this substance as uraninite but has recognised it from Liebenberg's description. It occurs as blebs, wispy masses and veinlets in the matrix (Pls. X, XI). Galena is usually associated with these bodies. The colour in polished section is light grey, variable and under crossed nicols it is isotropic with rich brown internal reflections. In ordinary light the appearance is similar to much of the leucoxene but the two can be distinguished once the nicols have been crossed. Liebenberg (1955) mentions the presence of radioactive leucoxene in the Vaal Reef and some of this may be subject to confusion with the secondary uraninite.

Where not much migration has occurred the original grain boundaries can easily be distinguished. The secondary uraninite grains are often partially replaced by various opaque minerals such as pyrite, chalcopyrite and pyrrhotite.

From the evidence of the polished sections the alteration or reconstitution of the uraninite took place at a relatively early period in the history of the blanket.

Thucholite.

This carbonaceous substance is usually present in the Vaal Reef in one or both of two forms: as individual "warty" granules up to 1mm. in size (Pls XIV, XV), and as seams with a columnar structure, usually less than one-tenth of an inch thick but exceeding one inch in exceptional cases. Occasionally, short thucholite veinlets are observed, made up of contiguous granules of the substance.

Thucholite was not found in reefs that did not contain uraninite. It almost invariably includes uraninite fragments and when this is not so the former existence of uraninite is indicated by a fine dusting of galena specks.

In ordinary light the substance is light grey in colour with a tinge of brown. As the colour is rather variable a mottled effect is created. The thucholite is very striking between crossed nicols when it is strongly anisotropic and displays a most interesting variety of tones. The appearance is much the same as that shown by serpentine in thin section between crossed nicols.

The thucholite usually occurs at the base of the reef but may also occur within the reef or at the top. Some localities are known where up to three seams are developed in the reef.

The columnar structure already referred to is well displayed in polished section. In transverse section these columns occur as individuals which have a hexagonal shape due to pressure effects. The columns generally have similar widths. Their form is considered to be the result of metamorphism.

Pyrite is fairly common in thucholite, where it is earlier and has suffered replacement. Gold is more abundant in association with thucholite than it is with other minerals. The gold is found coating thucholite granules and along the contacts between the columns.

Thucholite appears to be younger than most other constituents except pyrrhotite, skutterudite and probably gold.

Galena.

This mineral appears to be of radiogenic origin as it is found in close association with uraninite, usually as a fine speckling in uraninite grains (Pl. XV). It is found

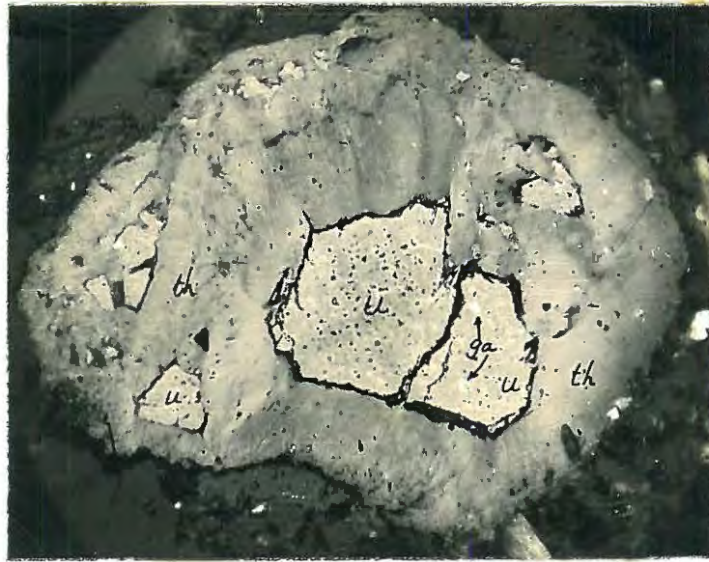


Plate XV: Vaal Reef. Slightly fractured uraninite grain (u) and several smaller uraninite fragments in a thucholite granule (th). White speckling in the uraninite and thucholite is radiogenic galena (ga). Polished section,  $\times 352$ .



Plate XVI: Mineralized foreset, Vaal Reef. Cracks in pyrite (pale grey) and chromite (darker) caused by expansion of radioactive zircon (zrn). Polished section,  $\times 88$ .

only rarely with chalcopyrite as small, rounded inclusions in pyrite and in one specimen occupies part of the boundary between a rounded pyrite grain and a later pyrite overgrowth. Galena occurring in this manner may be quite different from the radiogenic galena and thus of a different age, probably the same as that of the chalcopyrite.

#### Brannerite.

Only one grain of this mineral was encountered. It is grey in colour in ordinary light with a rather low reflectivity and shows weak, internal reflections. The grain had a rounded shape and had taken a rather good polish, showing no decomposition nor secondary effects.

The mineral was identified by a method of refractive index determination in reflected light as advocated by Ealos (1965). Standards used for drawing a calibration curve were sphalerite, corundum, cassiterite and rutile and the refractive index obtained was 2.285. Davidson (1957) has referred to the possibility of brannerite being present in the reefs of the Witwatersrand System.

#### Gold.

Gold may be common as anhedral, hackly grains in the reef matrix. It is authigenic in its present form. In addition to occurring as free grains it coats pyrite grains and thucholite. Its size reaches 0.6 x 0.17mm.

Gold often replaces pyrite and replacement textures are common. It also replaces secondary uraninite. Polished sections of gold-bearing thucholite also contain skutterudite which is later than, and replaced the gold. Chalcopyrite, on the other hand, is earlier than gold and is replaced by it.

#### Nickel or Cobalt Arsenide or Sulphide.

This mineral is not common but was found to be widespread and is present in several polished sections. From the optical properties and reflectivity value (53 per cent) the mineral could be cobaltite, gersdorffite or maucherite. It generally occurs as small, rounded to irregular grains which have suffered a certain amount of

fracturing. No intergrowths with any other minerals were observed. Liebenberg (1955) has found that gersdorffite in the Vaal Reef is often accompanied by a cobalt-bearing variety.

#### Skutterudite

This mineral always occurs as late, anhedral grains and is associated with gold. It was found in very few polished sections. The mineral also occurs as fine networks of veinlets surrounding gold or pyrite and is later than gold.

#### Linnacite

The identity of this mineral could not be confirmed. It occurs as a late mineral rimming pyrite grains and has a lower reflectivity than skutterudite with which it may be confused. The colour is pale whitish greyish-pink. The mineral did not occur anywhere in sufficient quantity to permit removal for identification.

#### Danaite

A very small amount only was encountered. The grains were fairly rounded, twinned and showed only slight anisotropism. Ramdohr (1958) has stated that the arsenopyrite he studied in the reefs is more correctly called danaite or glaucodot than arsenopyrite. As the grains were only weakly anisotropic the term danaite is preferred. Unlike the Vaal Reef, the Main Reef and Main Reef Leader contain a very constant amount of arsenopyrite (Viljoen, 1963).

#### Niccolite

Niccolite was encountered in only one polished section where it is found as thin lamellae in a fan-shaped aggregate of pyrrhotite laths and which was easily recognised by its strong anisotropism.

#### Pentlandite

Pentlandite is very uncommon and always occurs with pyrrhotite and chalcopyrite with pyrite normally being present. The mineral appears to be present in the form of a eutectic or exsolution intergrowth with pyrrhotite and does not occur as the flame-like lamellae described by Ramdohr.

### Magnetite

Magnetite is not common in the Vaal Reef. One particular occurrence may be described: a slightly rounded grain was observed completely enclosed in a small quartz pebble. This grain must have been present in the pebble at the time of deposition. Along cracks and around the edges the magnetite has altered to haematite.

In addition to the descriptions of the heavy minerals (p53) the following comments may be added from observations in polished section:

### Zircon

Zircon grains are detrital and are rounded to varying degrees. Zoning is present in a large number and is seen better in polished section than in heavy mineral concentrates. A high proportion of grains are fractured in situ but the various fragments have not moved far apart. The fractures are normally filled with matrix material, occasionally with pyrite and, rarely, with gold.

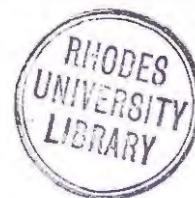
A specimen cut from a pyrite replacement body contained zircon grains completely surrounded by pyrite (Pl XVI). The pyrite immediately surrounding the zircon is badly cracked. The zircon appears to be metamict and the radioactivity has caused expansion, resulting in radial cracks being developed in the pyrite. This phenomenon was noticed only when hard, brittle minerals like pyrite enclosed zircon grains. The altered zircon is probably cyrtolite (Liebenberg, 1955).

### Chromite

Chromite is an original detrital mineral. The shape of the grains varies from well-rounded circular and oval to triangular and octahedral with very little rounding. Randolm (1958) states that some of the chromite appears to have been transported over very short distances.

The mineral takes a better polish than pyrite. Dark reddish-brown internal reflections can be seen on careful inspection.

A certain amount of fracturing of the grains has occurred. It is not certain whether some of this could be due to growth of adjacent pyrite grains.



### Leucoxeno

This mineral is found as rounded masses, irregular grains, short veinlets and wisps in the reef matrix (Pl. XI.) In ordinary light the colour is grey while under crossed nicols it varies from whitish to yellow-orange. Rutile is generally associated with leucoxene in the form of thin, needle-like crystals.

Variations in composition of individual grains can be seen from the change in reflectivity in different parts of the grains. This could be due to the particular composition of the original mineral and manifests itself in a greater or lesser concentration of rutile.

No original ilmenite or titanmagnetite was observed. Gold was observed on occasion as tiny specks in leucoxene grains. Formation of the veinlets occurred after crystallization of overgrowth pyrite.

### Rutile

Rutile is found as masses of authigenic needles with rounded detrital grains being relatively uncommon. Those grains which are detrital are normally repeatedly twinned and up to four directions of twinning were observed.

Some rutile grains are enclosed in pyrite grains. These are probably older than the pyrite. The authigenic rutile needles have formed after fracturing of pyrite grains.

### Paragenesis

The oldest minerals are the allogenic constituents such as zircon, chromite, original titanium minerals, gold, rounded pyrite, uraninite and probably brannerite.

The uraninite may be detrital as envisaged by Liebenberg (1955), or may have been precipitated in the form of discrete particles from dissolved uranium in the water of a sedimentary basin in a reducing, stagnant environment (Nel, 1960). The author found very few whole, rounded grains which could indicate that the grains were detrital, the majority of the grains were fractured or replaced by thucholite. Keen (1961) has suggested a modification of the theory put forward by Nel whereby the precipitated uraninite was redistributed by wave action so as to account for the hydraulic equilibrium between uraninite and other heavy mineral grains.

It is felt that the rounded pyrite may well be detrital in view of its form and early age.

In a reducing environment sulphide ion, rising upwards from Lower Witwatersrand shales, may have permeated through the blanket resulting in the formation of pseudomorphs and the growth of concretionary pyrite and porous pyrite. It is possible that the rounded grains referred to are pseudomorphs after original iron-bearing minerals, e.g. magnetite which is surprisingly and significantly rare in heavy mineral concentrates of the Vaal Reef.

This stage was followed by one during which the above grains were fractured, either as a result of the compaction due to overlying sediments or metamorphism. Subsequent to this a further influx of sulphide ion took place, resulting in the crystallization of overgrowth pyrite on the rounded and porous grains and this was probably largely contemporaneous with the crystallization of the irregular pyrite which filled cracks and replaced earlier pyrite. Some gold was enclosed at this stage and remained in the pyrite. The origin of these sulphide solutions is not known and remains a problem. A certain amount may have been introduced by dykes while some of it may have been derived from re-constitution of the detrital pyrite.

Minerals like danaite and gersdorffite could have been formed at this time but not enough information is available on these minerals for an accurate estimate to be made of their place in paragenetic order.

At a later stage thucholite was formed and gold and pyrite were enveloped during its growth. The thucholite and uraninite occur together, ". . . the thucholite originated by irradiation of gaseous and/or liquid hydrocarbons by the uraninite. . . ." (Liebenberg, 1955), or the hydrocarbons were originally present in the form of decayed algal material as envisaged by Nel (1960) and Snyman (in press). Strydom (personal communication) has suggested that the hydrocarbons were derived from original organic material in the Lower Witwatersrand shales.

This stage was followed by the alteration or re-constitution of the uraninite to secondary uraninite. At this time remobilization of leucoxene, which had formed from an original titaniferous mineral (ilmenite, titan-

magnetite or sphene) probably took place. The crystallization of bunches of authigenic rutile needles may have occurred at the same time.

Once these changes had taken place, the secondary uraninite and other minerals were replaced by chalcopyrite and pyrrhotite. The chalcopyrite appears to have crystallized before the pyrrhotite. Simultaneously, and for a short time after, gold crystallized and was replaced by the latest crystallizing minerals, skutterudite and linnaeite.

### 3. The Heavy Minerals.

Heavy mineral analyses were carried out on four samples of the Vaal Reef. The method has been described above. In the tables all opaque minerals, excluding gold, are grouped together as these were not readily identifiable with petrological and binocular microscopes. Furthermore, all sulphides dissolved during the nitric acid treatment.

Besides these opaques, the minerals identified in the concentrates were chromite, leucoxene, zircon, monazite, magnetite, sphalerite, tourmaline and fluorite.

Chromite, leucoxene and zircon occur as rounded grains of approximately the same size but are larger than in the quartz wackes. Tourmaline occurs in the same way as in the quartz wackes while magnetite occurs in very small amounts as partly rounded octahedra and cubes.

Monazite was found to be fairly common in the Vaal Reef as well rounded, greyish-brown grains with a resinous lustre, usually filled with tiny inclusions. Their size is similar to that of zircon. Several monoclinic, prismatic grains were encountered which had not suffered much rounding. The refractive indices determined were  $\alpha = 1.800$  and  $\gamma = 1.845$ , using phenyl di-iodoarsine as the immersion medium.

Sphalerite was found in one Vaal Reef concentrate as yellowish grains with a resinous lustre. The mineral is probably authigenic and is of no quantitative importance.

Pale green fluorite, probably also authigenic, was found in one heavy mineral concentrate. It too is of no quantitative importance.

Table 13.

The percentage of heavy minerals in the Vaal Reef (including opaques) and the percentage of opaque sulphides (mainly pyrite) in the heavy mineral suites.

Sample No.	H.M.s in V.R.	% opaques in concs.
1	8.5	96
2	9.4	95
3	8.9	95
4	6.9	98

Table 14.

Relative weight percentages of heavy minerals in the Vaal Reef; opaque sulphides excluded.

Minerals	Sample Nos.			
	1	2	3	4
chromite	33.8	21.0	17.4	14.9
leucoxene	1.0	48.0	54.1	25.8
zircon	27.5	25.1	23.4	24.1
monazite	5.3	3.6	1.5	18.6
magnetite	-	Tr.	-	-
gold	32.1	0.1	-	14.1
sphalerite	0.3	-	-	-
tourmaline	-	1.3	3.1	2.5
fluorite	-	0.9	-	-

The results show that there is a considerable variation in the relative proportions of the heavy mineral in the Vaal Reef and that the minerals recorded are similar to those found in the overlying and underlying quartz wackes.

The minerals which, by virtue of their relative importance, should be included in a detailed, regional, quantitative study of heavy mineral distribution, like that performed by Viljoen (1963), are zircon, chromite, leucoxene and monazite.

#### 4. The Silver content of Gold in the Vaal Reef.

Various studies of the silver content of gold ores have been published. Those dealing with Southern Africa include work by Eales (1960), Hargraves (1961) and von Rahden (1965). Hargraves' and von Rahden's work covered the conglomerates of the Witwatersrand System while Eales' studies centred on the hydrothermal gold deposits of

Southern Rhodesia although he included a discussion on the Witwatersrand gold ores, mentioning various parallels between the gold/silver relationships of hydrothermal and Witwatersrand ores.

Accordingly it was decided to ascertain whether any relationship existed in the Vaal Reef and if so, why. To this end the author collected 80 samples from selected areas underground for gold and silver assay and was given a further 240 assay results by the Assay department of the mine.

The relationship between the gold and silver contents can be expressed graphically (Fig.12) and it is not haphazard. A plot of gold value, in pennyweights (dwts) per ton against silver in dwts is linear with a relatively small divergence from the mean line.

The composition of gold in ores is commonly stated in terms of fineness. By definition, fineness in the metal is  $\frac{1000 \times \text{Au}}{\text{Au} + \text{Ag}}$  but the term "apparent fineness" is used here as

other minerals which could contain a small amount of silver (e.g. galena) are present in the ore, and further, the dross content has not been excluded.

There is a considerable variation in apparent fineness over the entire mine, the range being from 715 to 965. Furthermore there is a fair variation in fineness between individual samples from the same stope. Fig. 13 shows the result of a plot of apparent fineness against grade of ore in dwts per ton of gold. The curve shows similarities to curves plotted by other workers, e.g. Eales (1960) and von Rahden (1965), and indicates that higher grade ore is of greater fineness (i.e. contains proportionately less silver) than low-grade ore and that in no case is high-grade ore of low fineness. Thus, the higher the grade the less the silver percentage and vice-versa. Such an anti-pathetic relationship has been reported by Lawn (1924) and Prentice (1939). Both von Rahden (1965) and Richards and Rubidge (1950) have commented on the fact that below a certain grade the gold contains appreciably more silver. In Fig. 13 the critical range is 12 - 20 dwts. Above this value the apparent fineness levels off at a plateau value of 932 fine. With regard to the Vaal Reef, Hargraves (1961) states that the silver content of gold varies on either side of the Kromdraai fault. He states that the "disparity on opposite sides of the fault is presumably in some way related to the displacement of the fault". The

disparity in silver contents could be explained by the fact that the reef in his "shallow" area (SE of the fault) is generally thicker and includes "Pyritic grits" of low value, thus rapidly increasing the silver content, while on the down-throw side of the fault the reef is normally thin and low-value "pyritic grits" are usually separated from the reef by intervening quartzite and are not sampled for assay.

In order to ascertain whether fineness is a function of depth of burial, a graph of fineness vs. depth (as measured from a 6000 feet datum) was drawn up (Fig. 14). The results indicated that there is no obvious relationship, in contrast to the work of Hargraves (1961). His results are, however, in any event open to question as discussed by von Rahden (1965).

What is the cause of the systematic variation in silver content of the gold? Four alternatives may be considered:

- a. There may be base minerals which contain a small amount of silver,
- b. Silver could occur in native form or as some other mineral in the Vaal Reef,
- c. The variation may be due to hydrothermal effects,
- d. Sedimentary control could give rise to the variation.

a. Possible silver-bearing minerals are chalcovrite, sphalerite and galena. The former two minerals are not common in the Vaal Reef and it is unlikely that the large variations in apparent fineness could be due to these minerals. Galena, on the other hand, is fairly common, being associated with the alteration of uraninite and thus almost all of radiogenic origin. It is not likely that this galena would contain much silver, unless the silver became incorporated with the galena during the recrystallization of gold. However, it is not clear why silver should show a preference for galena rather than gold during recrystallization. Edwards (1960) mentions that at room temperature galena can accommodate only 0.1 per cent silver in its lattice.

A plot of apparent fineness vs  $U_3O_8$  (Fig. 15) is similar to that of Fig. 13. This is not unexpected as the gold and uraninite contents vary sympathetically. The graph shows quite clearly that increase in uraninite content, and therefore in galena content, is not accompanied by a decrease in fineness.

b. Von Rahden (1965) has found silver minerals in the Ventersdorp Contact Reef but the present study has failed to reveal the presence of such minerals in the Vaal Reef.

c. Eales (1960) points out that there are very few general rules regarding fineness applicable to hydrothermal deposits. For example, fineness may increase or decrease with depth, grain size etc. He explains the variation in fineness as being due to the varying solubility of silver in gold fluids at different stages in the crystallization of gold. The author did not carry out a study of the variation in fineness among individual grains as seen in polished section as this does tend to be rather subjective. Several of the facts, e.g. the low fineness of gold in low-grade ore, can be explained by Eales' hypothesis.

d. The fourth case to consider is the effect of varying sedimentary conditions. Two points may be considered:

1. In high-grade reef the fineness is a result of the amount of reworking the reef has undergone, the gold having been leached of silver during the concentration process. In low-grade reef, reworking, and thus leaching were less, resulting in a lower fineness. However, the effects of reworking on the silver content of gold have not been fully investigated and von Rahden (1965) has conducted experiments which throw doubt on the efficacy of differential leaching of silver.

2. Fineness of individual grains may be a reflection of the fineness in the original source rocks. The specific gravity of pure gold is 19.3 and that of pure silver 10.1. Therefore, the lower the fineness, the lower the specific gravity. Thus, where currents were stronger and reworking of gold and heavy minerals took place, the heavier gold could have remained while the lighter gold was removed.

Prentice (1940) and Young (1917) state that the purity of gold increases with the increase in grain size. It is not certain whether this is important as the gold has suffered redistribution so that the present size may not be a true reflection of the original grain size. If the above is true then the larger (purer) particles would tend to remain behind while the lighter gold was removed. Accumulation of larger particles would result in a higher grade. The variation in fineness between samples from the

same stope can be explained as follows: in one spot some larger gold particles of low fineness were deposited together with smaller particles of purer gold while in another spot only small particles of relatively high fineness accumulated.

It is accordingly suggested that the observed fineness variations are due to distribution of the gold by currents of varying strength and that the fineness of individual grains is a reflection of the composition in the original source rocks.

#### 5. The Uranium/Gold relationship in the Vaal Reef

Several graphs have been drawn up to illustrate the relationships, and variations in them. Mine assays of the uranium content of the Vaal Reef are given as pounds  $U_3O_8$  per ton of ore. These values have not been converted back to uraninite for the purpose of the discussion.

Fig. 16 is a plot of  $U_3O_8$  vs. gold from high-grade areas of the mine, while Fig. 17b is a similar plot for low-grade areas. There is a definite increase in the ratio  $U_3O_8/Au$  in the low-grade areas indicating that the uraninite is more widely, or rather, more evenly spread than the gold. The boundary lines of the plotted points follow a curved trend, showing that the  $U_3O_8/Au$  ratio continually decreases with increasing grade. It is more convenient to use these boundary lines than the best centre line owing to the wide spread of points. Examples of the ratios (as shown by the boundary lines) are as follows:

High-grade reef	1.41/10
Low-grade reef	8.9 /10.

Fig. 17a gives a plot of the  $U_3O_8$  values of the pyritic grits overlying the Vaal Reef which form the greater part of the Vaal Reef Sub-zone in the No. 2 Shaft area. These grits are characteristically of very low grade and it is interesting to note that the  $U_3O_8/Au$  ratio is greater than in the case of the low-grade reef. The basal portion of the Vaal Reef in the No. 2 Shaft area is often of higher grade than the usual Vaal Reef and here the ratio is 0.8/10.

In order to ascertain how such  $U_3O_8/Au$  ratios vary laterally in the reef and in the overlying pyritic grits in the No. 2 Shaft area graphs were plotted of this ratio vs. sample interval.

The results are seen in Fig. 18. It is immediately clear that each individual conglomerate band has a characteristic  $U_3O_8/Au$  ratio and that this tends to remain fairly constant. The graphs are complicated by the lenticular nature of the siliceous quartzite lenses and transgression of the conglomerate bands. The  $U_3O_8/Au$  ratios are plotted on a logarithmic scale for convenience.

The question arises as to why the ratio remains constant in any one band and why it varies between the different conglomerate bands. In any one reef band the conditions prevailing at the time of deposition were more or less constant and the ratio is a reflection of this (with the condition that the grade remains at approximately the same level). Where the grade is lower and concentration or reworking has taken place to a lesser extent, the  $U_3O_8/Au$  value increases. Thus, in Fig. 18 the highest-grade conglomerate has the lowest ratio, while the overlying poorly-mineralized grits show higher ratios. These pyritic grits are less well-sorted, composed of smaller pebbles, often have a less siliceous matrix and are intercalated with lenses of quartzite. These facts point to more variable conditions and less prolonged reworking and hence the different ratio.

It has been established that the  $U_3O_8/Au$  ratio decreases as the payability or grade of the ore increases. Thus it appears that the uraninite was less readily concentrated relative to gold in the areas of greater reworking than in areas where less reworking has taken place. The uraninite being of lower specific gravity than gold, has a wider distribution than the latter although assays show that more uraninite was deposited in higher-grade areas than in low-grade areas.

Simpson's (1952) results of radiometric logging have indicated that there is a certain amount of radioactivity in all the sedimentary rocks of the Witwatersrand System in this area.

A useful application is that the  $U_3O_8/Au$  ratio can give one an idea of the payability of a reef in the case of boreholes where full core recovery has not been obtained. As there is a critical value of this ratio above which the grade is low, by ignoring the assay value itself and working

with the  $U_3O_8/Au$  ratio alone, one can arrive at an accurate estimate of the payability of the reef, e.g. if the point in question plots outside the boundary line in Fig. 16 the reef is probably of low-grade. However the converse is not true, i.e. if the point plots inside the boundary line it need not indicate high-grade ore.

When a thucholite seam is present in the Vaal Reef (and this is very often the case) it is unusual that full core recovery is obtained and this application of the uranium/gold ratio should prove useful.

CHAPTER 3THE INTRUSIVE ROCKSGeneral

A study of the various intrusive rocks in the mine was carried out with a view to classifying these rocks into various types and possibly assigning relative ages. In the past very little attention has been paid to the igneous rocks intrusive into the Witwatersrand System in the Klerksdorp area although a considerable amount has been published by various authors who have examined the post-Witwatersrand intrusives in other parts of the goldfields, notably Antrobus (1956), Brandt (1949), Ellis (1940, 1944, 1946, 1947), Winter (1957). Nel (1935, 1939) and Wilson and others (1964) included discussions on the intrusives in papers dealing with the geology of the Klerksdorp area. Wilson and others (1964) divide the intrusives into post-Transvaal and Ventersdorp rocks. Examples of post-Transvaal dykes are kimberlite, Karroo dolerite, Pilansberg-type dolerite and porphyritic diabase while Ventersdorp intrusives are mainly diabases and epidiorites. A table of the intrusives into the Witwatersrand System as given by various authors has been drawn up and is presented below (Table 15). pp. 62 - 63.

An attempt was made to collect samples of all intrusives in the mine. This was not always possible as certain worked-out areas were inaccessible. Sampling procedure included collection of specimens of contacts and country rock in addition to the intrusives themselves. In addition, samples of the same intrusives were collected at widely-spaced points along strike and down-dip, in order to determine whether variations existed in any one type. According to Antrobus (1956), "These intrusives maintain their characters over very wide areas, though the degree of alteration may vary very rapidly". This is largely confirmed by the present study except that the degree of alteration varies little.

Author and Locality	Pre-Venters-dorp	Venters-dorp	Post-Vent-ersdorp	Post-Vent / Pre-Transv.	Pre-Trans-vaal	Post-Trans-vaal	Post Tvl./pre Karroo	Post-Karroo/pre-Cret.	Cretaceous
Antrobus (1956) O.F.S.		yellow porphyry, acicular Ventersdorp	quartz diorite shonkinite					dolerite	augite-lamprophyre, kimberlite
Antrobus & Whiteside (1964) F.E.R.	uncertain	diabase (2 ages) quartz porphyry, granophyre, norite		ilmenite diabase	epidiorites (?)		syenites, Pilanesberg dolerites	dolerites	
Brandt (1949) F.E.R.		quartz diabase		ilmenite diabase	norite granophyre		syenites	dolerites	
Coetzee (1961) O.F.S.		diabase, pyroxene-bearing diabase				lamprophyre		dolerites	kimberlite
De Jager (1964) F.E.R.	quartz-sericite rocks	quartz-dolerites			ilmenite diabase ?	ilmenite diabase ? syenitic types		dolerite	
De Kock (1964) F.West R.	silicified types, chloritoid-bearing types	altered diabase amygdaloidal diabase porphyritic diabase					several composite types, albite syenite, shonkinite		

TABLE 15

Jacob (this thesis) Vaal Reef		quartz diabases, amygdaloidal diabase	mela-micro- -diorites, mottled microdiorite			Carbonatite		lamprophyre	
Nel (1935) Klerksdorp- Ventersdorp		shaly types			quartz dol- -erite, augite por- -phyrite, feldspar porphyry		hybrid rocks		kimberlite
Nel (1939) Klerksdorp- Potchefstroom					augite por- -phyrite, feldspar porphyry, quartz dol- -erite		diabases, alkali granite, syenite, diorite, enstatite granophyre	dolerite	kimberlite
Wilson et al (1964) Vaal Reef Basin		non-porphyr- -itic diabase, epidiorite				porphyritic diabase, Pilanesberg- type doler- -ite		dolerite	kimberlite

TABLE 15 (Continued)

Each intrusive was examined underground and the following features were noted: colour, granularity, shape of intrusion, thickness, strike, dip and dip direction, contact phenomena, effect on country rocks, amount and composition of veinlets, degree of mineralization, flow structures, degree of alteration, displacements of country rock and presence of phenocrysts and amygdaloes. Altogether 230 samples were collected for macroscopic and microscopic study.

At the outset an attempt was made to distinguish the various types in hand specimen as this would prove most practical. This method was largely successful. In most instances doubtful cases could be resolved under the microscope. However there are several intrusives which appear to be transitional in character or which show characters which make classification doubtful. The intrusives were all originally intermediate, basic or ultrabasic in composition, acid types not having been found. Due to the degree of alteration a detailed classification was not possible so that descriptive names, rather than petrological, have been given in some cases.

The great majority of intrusives are dykes. Sills are subordinate but unpredictable due to their often transgressive nature.

From an inspection of the logging of 39 surface boreholes the percentage intrusives intersected in the Witwatersrand, Ventersdorp and Transvaal Systems was seen to be as follows: Witwatersrand System 6.2 per cent, Ventersdorp System 0.3 per cent and Transvaal System 0.27 per cent. With regard to the Ventersdorp System the figure may be somewhat low as intrusives are not always immediately distinguishable from the lavas.

The types so far recognized in the mine are as follows:

1.	Quartz diabase	<u>Specific gravity</u>
	a. porphyritic,	} 2.85
	b. porphyritic "feathery",	
	c. uniform or non-porphyritic.	
2.	Amygdaloidal diabase.	2.84
3.	Ilmenite mela-microdiorite.	2.98
4.	Mottled microdiorite	2.92

5. Olivine lamprophyre	2.32
6. Carbonatite	2.92

The various types of intrusives may be seen in Fig. 19.

### Description of the Intrusive Rocks

#### 1. Quartz diabase

##### General:

By far the greatest number of intrusives are of this type. Three varieties can be recognised, and the porphyritic variety is more common than the non-porphyritic. The term "porphyritic" refers to its appearance in hand specimen and is perhaps a misnomer because the fresh rock would probably not appear as such. This porphyritic variety is a pale grey to grey-green colour with small, stubby, lath-shaped phenocrysts up to 1.5 mm. which are chloritized to varying degrees and are set in a microcrystalline, pale-coloured groundmass. The "feathery" variety can be recognised with the aid of a hand-lens. The texture is due to fine, acicular crystals, outlined by whitish, probably leucocratic material in the groundmass surrounding the chloritized phenocrysts. The non-porphyritic variety is also pale grey-green but in this case alteration has obscured all previous textures. Because of their inherent similarities and modes of occurrence, the three varieties are considered to belong to the same type. In the literature, quartz diabases from the East Rand have been described by Ellis (1940) and Brandt (1949).

- |   |                                  |
|---|----------------------------------|
| a. <u>Porphyritic quartz diabase</u> and  | } <u>Characteristic features</u> |
| b. <u>Non-porphyritic quartz diabase:</u> |                                  |

These will be described together. Specimens of the latter appear shaly or uniform to the naked eye but under the microscope very faint palimpsest igneous texture is visible in reflected light. Sills are known but are not common.

The dykes do not show any definite trend direction although there is a suggestion of a northerly to north-westerly trend and those dykes which strike in an approximately northerly direction, and which are not vertical, generally dip towards the east, while those which strike roughly east-west dip towards the south. Dips of the dykes

are steep, varying between  $75^{\circ}$  and  $90^{\circ}$  although occasionally lower angles of dip are encountered. These dykes are normally thin, about 10 feet thick, and do not vary much in thickness along length or down-dip. One 10 feet thick dyke widens to 40 feet in one part of the mine but this is exceptional. Often thickness appears to vary considerably over short distances but this effect is caused by later faulting with either different strike or dip. These dykes may split, to join further on.

More than 60 per cent of these dykes show shearing on both contacts while only 17 per cent have both contacts chilled. The chill-zone, when developed, is very thin, about 1 inch, although chill zones of 4, 7, 9 and 11 inches were recorded. The contact is regular when it is chilled.

Metamorphic effects on the quartzites are slight. The most common effect of intrusion is chloritization of the country rock matrix with the zone of complete chloritization varying from half an inch to 7 inches. The affected rocks appear almost black. A further zone of partial chloritization results in the rocks acquiring a greenish tint. Where the country rock was originally a faintly speckled quartz wacke before intrusion, it may become more coarsely speckled for several inches. Several exposures showed vitrification of the quartzites up to 3 inches from the contacts.

The dykes show a variety of veining phenomena. They are commonly highly veined by veins of milky quartz, chlorite and calcite. Pyrite may also be a constituent of such veins. The vein-quartz occurs as a fine-grained mosaic while calcite and chlorite show comb structure with crystal growth at right angles to the walls of the veins. The quartz may be partly replaced by later calcite. One particular dyke intersected in 54 26 cross-cut South No. 1 showed a very striking reticulate pattern of veining.

There is a greater variety of mineralization associated with the above varieties than with other types. Very few dykes appeared to be barren of sulphide mineralization. The most common sulphide is pyrite which occurs both as specks and as tiny veinlets. Pyrrhotite, chalcopyrite and galena are present in small amount. Oxides such as leucoxene are common and have formed from original ilmenite.

Petrography: The size of the chloritized laths, compared to the grain size of the groundmass allows the term "porphyritic" to be used in a loose sense (Pl. XVII). The rocks are holocrystalline, aphanitic and may, in the past, have shown ophitic or subophitic texture but this is no longer visible.

Due to the degree of alteration, the original minerals are no longer determinable and in thin section the rock consists of a fine-grained mass of calcite, chlorite, quartz and other secondary minerals. The palimpsest igneous texture may be seen in ordinary light or in reflected light but under crossed nicols the texture disappears completely. The non-porphyritic types may show the original outlines of laths very weakly in reflected light.

The phenocrysts show varying shapes from perfect lath-shape or square to oval (pl. XVII). The lath shape is most common, length being two to three times the width. Their size varies up to 1.5 mm. although occasionally dykes were encountered which showed two distinct size-ranges of phenocrysts, the larger being 6 mm. The average length of the laths is 0.5 mm. and they rarely show any parallel orientation except near the contacts. The laths are now composed of saussurite which has been chloritized to varying degrees, in some cases completely, when the chlorite occurs as tiny flakes. Often laths composed of chlorite and sericite were noted, the latter's presence being due to its resistance to chloritization. Calcite replaces the laths in part although it usually shows a preference for the groundmass. The original lath shapes can often be seen through the calcite masses in ordinary light. The abundance of laths in thin section may reach 60 per cent but is dependant on the degree of alteration.

The groundmass, grain size 0.01 to 0.03 mm., is a fine-grained mass of secondary minerals, these being calcite, chlorite, quartz, sericite, leucoxene and, rarely, epidote. The carbonate appears to be the youngest mineral. It is found as tiny grains, granular aggregates and large and small rhombs. Even late quartz is replaced by the calcite. Several thin sections showed almost complete calcitization of the groundmass.



Plate XVII: Relict igneous texture in quartz diabase. Chloritized, calcitized and saussuritized feldspar laths set in a quartz-chlorite-calcite groundmass. The texture disappears completely when the nicols are crossed. Polarized light, x 32.



Plate XVIII: "Feathery" quartz diabase. Chloritized feldspar crystals in a matrix of chlorite, quartz and carbonate. Black speckling is leuconene. Feathery texture well displayed. Polarized light, x 90.

Chlorite is normally the most abundant mineral in the groundmass. It is pale green, non-pleochoric and occurs as tiny flakes and flaky aggregates, presumably after pyroxene. The chlorite occurs in the following ways: 1.) as tiny inclusions in, or intergrowths with quartz, 2.) as aggregates of several fair sized flakes which may show a radiating structure under crossed nicols, 3.) as rare, large, individual, shredded grains showing cleavage, and 4.) as tiny anhedral flakes scattered in the groundmass.

Rather peculiar is the intergrowth of quartz and chlorite on a microscopic scale such that their relative amounts could not be estimated. This is perhaps due to incomplete unmixing of quartz and chlorite resulting from alteration of ferromagnesian minerals.

Sericite is often very common as tiny, scattered shreds although in the very highly altered rocks this is less common. The flakes may reach 0.2 mm. in size.

Quartz is usually common. The more highly sheared and veined the rock is, the more quartz is present. It has four modes of occurrence: 1.) clear pools in the groundmass, 2.) very cloudy-looking grains crowded with tiny inclusions of chlorite, 3.) possible micropegmatite, now mostly altered with sericitization, 4.) fine-grained mosaics in veinlets.

Much of the quartz was introduced by veins and some is derived from alteration of primary minerals while a certain amount was probably primary.

Leucoxene is the most common accessory. It occurs as tiny grains, size about 0.01 mm, scattered throughout the groundmass and these are a dull whitish colour in reflected light. Their shapes tend to be pseudo-octahedral. It is also found as larger skeletal crystals (less than 0.1mm.) and as thin, rodlike crystals which may be rutile in part. Rutile was found as small, rounded grains in one thin section, surely derived from the original titaniferous ore mineral.

The amount of leucoxene is small but may exceptionally reach 5 per cent. Later carbonate surrounds the grains but does not replace them. In many instances the leucoxene has recrystallized to sphene which is translucent

in transmitted light. The parent mineral was either ilmenite or titaniferous magnetite. Van Niekerk (1959) has described the occurrence of leucoxene and sphene in dykes of Pilanesberg age, where titaniferous magnetite alters to leucoxene while ilmenite remains unaltered.

Pyrite is commonly seen as an accessory mineral, usually as irregular grains and rarely as euhedral crystals.

Other uncommon minerals observed include epidote, which was seen in only two slides where it occurred as single, small grains which had probably separated from saussurite, and idocrase or clinozoisite, which was present in one thin section as fair-sized grains showing anomalous blue interference colours. Small red spots seen in one hand specimen were found to be related to carbonate distribution in thin section. They appear to be stains but could not be identified.

b. "Feathery" quartz diabase:

Characteristic features: This is a textural variety of the quartz diabase as seen from its field relationships and mineral assemblage which has probably followed a slightly different course of alteration and therefore shows textural variation. These dykes showed the feathery texture throughout their lengths.

This variety can be distinguished from those above in hand specimen with the aid of a hand-lens. It consists of chloritized and saussuritized laths in an aphanitic groundmass containing thin, acicular crystals which give rise to a feathery texture (pl. XVIII).

No definite trend direction is apparent but there is a tendency to strike roughly northwest. In such cases the dip is towards the northeast. Dykes trending at right angles to the above dip in a southerly to southeasterly direction. Dips are steep, approaching  $90^{\circ}$ , with an average of  $70^{\circ}$ . Thickness varies between 6 and 23 feet, is usually 15 to 20 feet. This is slightly thicker than the porphyritic variety.

Contacts are almost invariably sheared and in no case were both contacts found chilled. Chill zones, where observed, are very thin. The contacts are more highly altered than the centres, more calcitized and

contain more quartz. No original igneous texture can be distinguished in these zones.

For the most part contact phenomena are slight. complete chloritization of the country rock matrix, resulting in a black colour, may take place up to 10 inches from the contact. Incomplete chloritization, as evidenced by a pale green colouration in the quartz wackes, was occasionally observed. Very few contacts displayed vitrification of the quartzites.

In common with other types, intrusion of a dyke of this variety results in a bleached or pale yellowish colour being developed in the invaded rocks, sometimes up to as much as 30 feet from the contact. This is somewhat puzzling as thin sections of this bleached rock appeared to be very similar to sections of unaffected country rock. However the former does contain slightly more chlorite than the latter and this is probably the cause.

Quartz and chlorite veining are common in the dykes, in some cases abundant. Chlorite veinlets are thinner than the quartz veinlets. The dykes are usually mineralized to some extent although two dykes were encountered which appeared to be barren of sulphide mineralization. The most common sulphide is pyrite, in the form of veinlets associated with quartz and chlorite veins and as specks scattered throughout the rock. Galena and chalcopyrite were observed but are uncommon. Leucoxene is common and may occur as wisps giving emphasis to the feathery texture.

Three dykes showed flow structure near the contacts. Petrography: The appearance under the microscope is similar to the porphyritic variety except that in addition the groundmass contains long, thin, acicular crystals which give rise to the feathery texture and which may rarely have parallel orientation.

Again, the palimpsest igneous texture can be seen in ordinary transmitted light or in reflected light but not under crossed nicols. The laths reach 1.0mm. in size and may make up 50 percent of the rock. They have altered completely to saussurite which has then either suffered chloritization or been replaced by calcite.

The acicular crystals may be very abundant (pl. XVIII), perhaps making up 40 percent of a thin section. Their length reaches 1.0 mm. Secondary minerals make up these crystals, e.g. quartz, quartz interleaved with chlorite, chlorite-sericite mixtures and calcite and chlorite. Winter (1957) has described similar textures. He states that faint feldspar lines were obtained from X-ray information. The crystals are often bordered by thin, opaque wisps, white in reflected light, which allow the texture to be seen clearly in hand specimen. It is not quite certain what this substance is; perhaps leucoxene or an amorphous dusting. In the meladiorites the pyroxene which has altered to uralite shows a faint tendency for acicular shreds of uralite to produce a feathery texture. It appears likely that the acicular crystals are merely altered uralite fibres. The most common composition of these acicular crystals is a mixture of chlorite and quartz and this could be derived from the alteration of augite to uralite (Tyrrell, 1956). It is not impossible that this variety is slightly younger than the previous two varieties and that alteration has not advanced to the stage where the feathery texture is destroyed. It may also be that alteration of pyroxene to chlorite took place without the intermediate uralite stage in the non-feathery varieties.

The acicular crystals may make up part of the groundmass the remainder being a fine-grained (0.03 mm.) mass of chlorite, quartz, calcite, sericite and leucoxene interstitial to the laths and acicular crystals.

Quartz is present both as tiny grains filled with chlorite inclusions, resulting in a dirty appearance, and also as clear pools and veinlets which may replace chlorite. A small proportion of the quartz is probably primary.

Chlorite in the groundmass occurs as tiny flakes. It is pale green, non-pleochroic and may have a slightly high birefringence so that quartz and chlorite cannot always be distinguished when the groundmass is very fine-grained.

Calcite is a late mineral which replaces all other minerals except leucoxene and it is found as very tiny grains in saussurite, as larger, irregular granular aggregates and as perfect rhombs up to 0.2 mm. in size.

Sericite occurs as tiny scattered shreds in the groundmass and in laths of chloritized feldspar.

Identifiable epidote was not encountered.

Leucoxene, probably derived from ilmenite, was observed in several forms, e.g. diamond-shaped grains, needle-like grains and wisps.

Petrographic and field evidence links this with the porphyritic variety. It was probably contemporaneous with this variety but has followed a slightly different course of alteration.

## 2. Amygdaloidal Diabase.

Characteristic features: This type is very characteristic in hand specimen where it is either a pale grey-green or a dark green colour and consists of laths and amygdales set in an aphanitic groundmass. The amygdales are small (less than 0.5 cm.) and the colour varies between dark green and pale whitish-grey.

With one exception the dykes trend roughly north-east-southwest, that dyke trending at right angles to this direction. Dips are to the southeast, the exception dipping at  $80^{\circ}$  to the northeast. Dips vary widely between  $30^{\circ}$  and  $90^{\circ}$  although the dips along any one dyke do not vary more than  $20^{\circ}$  from one point to another. The average dip of these dykes is  $60^{\circ}$ .

This type of dyke is invariably thin. Their average thickness is 7 feet, the limits being 6 feet and 12 feet. Each dyke maintains a constant thickness.

For the most part the contacts are chilled, yet occasionally one contact is sheared while the other is chilled. The thickness of the chill zone does not exceed 10 inches and is usually 4 to 7 inches. In these chill zones whitish, circular segregations may occur which are extremely fine-grained and may contain numerous 0.5 mm amygdales. The patches are cryptocrystalline under the

microscope and are virtually opaque. Very tiny quartz grains and veinlets may be seen in these patches.

Effects on the host rocks are slight, the most common being chloritization of the wacke matrix up to a maximum of 7 inches from the contact. One exposure showed an apparent vitrification of the host rock for a very short distance.

Quartz and chlorite veining are not pronounced in this type. The variety of mineralization is poor. Pyrite is found as specks and as small cubes, while leucoxene is common as tiny grains, best seen under the microscope.

A certain amount of faulting is associated with these dykes. Throws are normally of the order of 5 feet. A throw of 30 feet is exceptional. One dyke fills an 8 foot reverse fault. Flow texture has not been observed in these dykes.

Petrography : Mineral assemblages and textures are similar to the quartz diabase with the addition that this type is amygdaloidal.

The amygdales, which may reach 5mm. in diameter, average 1.5 to 2mm. Their shapes are circular to oval and they occasionally join up. A concentric zoning, caused by variation of mineral composition can often be observed (pl. XIX). The minerals forming the amygdales are quartz, chlorite, calcite and sericite and in the larger amygdales these appear in varying combinations and positions relative to the centre. Smaller amygdales may consist entirely of quartz. Calcite replaces the amygdales in several thin sections. In such cases the entire rock has suffered calcitization. Anhydrous pyrite also commonly partly replaces the amygdales. Often the amygdales are bordered by small, rounded grains of epidote.

In hand specimen many amygdales are surrounded by microcrystalline grey haloes. Microscopically these are lath-free areas of quartz and chlorite. Occasionally these small, grey areas are developed without the central amygdale being present.

The lath-shaped, green crystals seen in hand specimen average 0.75 mm. in length but may reach 1.3 mm. They may be both short and stumpy or long and thin. Originally plagioclase, they now consist of saussurite or chlorite; calcite may replace these minerals. In addition to the laths, tiny rodlike or acicular crystals are seen, which resemble those in the feathery variety, consisting as they do mainly of quartz and chlorite which may be replaced by calcite. They are less well developed but probably have the same origin.

The laths are not as abundant as in the porphyritic variety. They do, however, make up 30 percent of the rock in several of the specimens studied.

The groundmass is very altered. Average grain size varies between 0.01 mm. and 0.05 mm. The minerals are calcite, chlorite, quartz, sericite, epidote, leucoxene, sphene and some plagioclase. Due to alteration, the nature of the plagioclase is indeterminable. The amount of epidote varies. In addition to epidote, zoisite is found as small, rounded, pale yellowish green grains.

Sericite is present as tiny shreds while chlorite occurs as irregular, pale green flakes which have low birefringence and are not pleochroic. The quartz is found as cloudy grains filled with tiny chlorite inclusions but is also found as clear pools. Calcite is younger than the other minerals and replaces them to varying degrees. Leucoxene is commonly found recrystallized as sphene and tiny rutile needles. The leucoxene and sphene are found as skeletal crystals, diamond-shaped crystals and wisps. Their size reaches 0.3 mm.

The rocks show textural and mineralogical similarities to the quartz diabases and may be a variety of this type. However there is less shearing and veining associated with these dykes and they may constitute a separate type. The amygdaloidal character suggests an affinity with the Ventersdorp lavas. The composition of the amygdales is similar to that in lavas but it is unusual for amygdales to be developed in dykes. The mechanism of formation is difficult to imagine. It appears that steam-filled bubbles were filled by later minerals of secondary character.

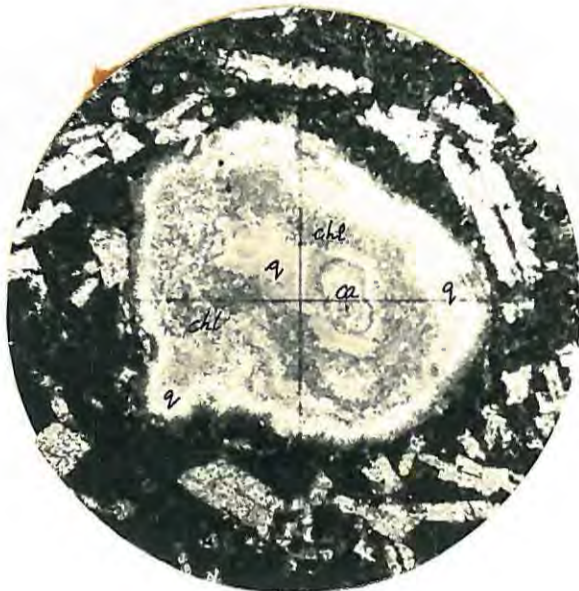


Plate XIX: Amygdaloidal diabase. Concentrically zoned amygdale consisting of carbonate (ca), chlorite (chl) and quartz (q) surrounded by saussuritized plagioclase laths and a chlorite and carbonate-rich matrix. Black speckling due to leucoxene. Polarized light, x 32.



Plate XX: Ilmenite mela-microdiorite showing skeletal crystals of leucoxene (black) surrounded by uralite and chlorite (ur), epidote (ep) and fine grained quartz and chlorite (q/chl). Polarized light, x 32.

Reference to amygdaloidal intrusives is comparatively rare in the literature but both Nel (1935) and De Kock (1964) have mentioned similar rock-types.

### 3. Ilmenite Mela-microdiorite.

Characteristic features: These dykes are dark green in hand specimen and contain abundant leucoxene after ilmenite and epidote, both of which are visible to the naked eye. The intrusives have<sup>a</sup> fresh appearance but are usually fairly altered when seen in thin section. They are not easily confused with other types.

The dykes show a definite northeast-southwest trend with a few exceptions striking at right angles to this direction. They show a tendency to wave or kink along their lengths. Their dips are towards the southeast at angles which vary considerably from  $10^{\circ}$  to  $90^{\circ}$  and are normally steep. They may form sills and often dyke-sill forms are developed. Thus their behaviour cannot always be predicted.

This type of dyke is invariably thick, the average being 30 to 40 feet. The thinnest dykes observed are 15 feet thick while the thickest approach 200 feet. Thickness does vary along the length of such dykes.

Fourteen dykes of this type were studied and in almost every case the contacts were chilled. No dykes showed shearing on both contacts and only three exposures showed shearing along one contact only. Chill zones are well developed and may be 18 inches thick. Their average thickness is 12 inches.

Metamorphic effects on the country rock are small. The most common effect is chloritization of the host rock matrix, resulting in a black to green colour. A rather bright green colour may be present up to 8 feet from the contact, when the wackes become paler and gradually grade to their normal colour. In some cases the contact could be made out only with difficulty. Vitrification of the contact sediments, due to some measure of recrystallization, is often noticeable although not common.

Three thin sections were cut of dyke/wacke contacts. The dyke material is aphanitic, highly altered with tiny

(0.2 mm) laths of saussurite developed parallel to the contact. Two of the thin sections showed development of chloritoid crystals of a rather pale green colour in the host rock. This mineral was not observed near the contact of any other type of dyke. Chloritoid is generally regarded as a stress mineral and is found in sediments which have suffered the earlier stages of dynamic metamorphism. It is also found in the early stages of regional metamorphism if the rocks have an abundance of alumina, e.g. kaolin, and sufficient iron oxide for its formation. It was also found away from the contact and appears not only to have formed as a result of intrusion of the dykes.

Between the chill zone and the typical dyke rock is a variegated, streaky zone of aggregates of small, whitish crystals of saussuritized plagioclase and calcite surrounded by green chloritic material. This zone is present in most of the dykes and is usually two feet thick. Parallel alignment of the crystals lends a streaky appearance to the rock in hand specimen.

Quartz veins, up to 3 inches thick, are common in the meladiorites while chlorite veining is subordinate. A small amount of calcite veining is also present.

The degree of mineralization is greater than in other types. Leucoxene after ilmenite is very common while magnetite is often observed but is not as abundant. The only sulphide observed is pyrite which occurs as well-developed cubes and pyritohedra, up to a half inch in size, and is also found in the form of thin veinlets. The amount and size of the pyrite crystals scattered throughout the rock is quite striking.

For the most part these dykes are not associated with any faulting although apparent displacements may be present due to thickness of the intrusions. The dykes do, however, follow fault planes for short distances, usually normal faults but occasionally reverse faults too.

Petrography: The dykes are phanocrystalline, fine-grained with an average grain size of 0.3 mm. In a few thin sections a subophitic texture may be recognised while in others the texture is intergranular. Plagioclase and pyroxene, the latter now altered to uralite and

chlorite, are the essential minerals.

The laths of plagioclase, 1 mm. long, are elongated or stumpy and have been saussuritized. This saussurite has segregated so that the following minerals become individually recognisable: calcite, sericite, chlorite, quartz and epidote. Due to the alteration, relatively few plagioclase laths were suitable for determinations of maximum symmetrical extinction angle. The angle obtained,  $21^{\circ}$ , indicates andesine.

Pyroxene, no longer present, has altered to either uralite or chlorite. The uralite is pleochroic from pale green to colourless, occurring as long fibres or fibrous aggregates with an extinction angle, cleavage to  $z = 25^{\circ}$ . Further alteration to chlorite may be partial or complete.

The chlorite is very striking under crossed nicols where it displays an anomalous purple interference colour. The mineral is more strongly pleochroic than the uralite, the colours being colourless and bright green. It occurs as fine-grained aggregates, scales and pseudomorphs after uralite. Chlorite-quartz intergrowths are seen as a result of alteration of the pyroxene.

Calcite is found as a constituent of the saussurite, as irregular granules up to 0.25 mm. and as late, fine-grained aggregates and veinlets which replace all other minerals except the opaques. In transmitted light the carbonate has a dirty brown appearance which appears whitish in reflected light. It is not certain what causes this.

Epidote is a very common mineral and, by its amount, may be diagnostic of this type. It is found as tiny grains, anhedral granular aggregates and as veinlets. Birefringence is high second order. The colour is pale yellow-green and pleochroism varies from this colour to colourless. Clinozoisite was recognised in lesser amount and as smaller grains.

Quartz is found in the rock as clear pools containing tiny, needlelike crystals of rutile, as anhedral grains in saussurite and as cloudy, anhedral grains filled with chlorite inclusions. It normally shows strain extinction.

Leucoxene may constitute up to more than 6 per cent of the rock. It is found as boxworks, diamond-shaped grains, pseudo-hexagonal crystals, long, thin, rodlike crystals, specks and anhedral grains, which can usually be seen with the naked eye in hand specimen (pl.XX). The mineral appears to be an alteration product of ilmenite, which is very rarely seen in the cores of grains. The crystal form suggests ilmenite, rather than titaniferous magnetite, to be the parent mineral.

Magnetite is widespread as anhedral masses, perhaps bordered by haematite, or as rounded grains. The grains are smaller and less common than leucoxene.

The rock therefore has a dioritic composition near the boundary between diorite and gabbro. Because of its dark colour the term meladiorite is suitable. Wahlstrom (1958, p.308) mentions the name belugite for similar rocks. The term microdiorite reflects the rather fine grain size of these hypabyssal rocks.

#### 4. Mottled Microdiorite.

Characteristic features: This is not as common as other types. It shows many similarities to the meladiorites and may be contemporaneous with these, having merely followed a different course of crystallization. The rock is not as dark coloured, however. The term mottled refers to its appearance relative to other rather uniform dyke rocks.

Too few of these are known for a definite trend direction to be established. A weak tendency to trend northeast is apparent. Dips of the dykes are variable, usually near  $90^{\circ}$ , with variations of up to  $20^{\circ}$  along such bodies. This type is often found as sills and transgressive sheets whose thickness is usually 25 to 30 feet but which varies considerably along their lengths.

Although occasionally one contact is sheared, the contacts are usually chilled, the chill zone of 1 to 12 inches not being as well developed as in the meladiorites.

The country rock is normally affected by chloritization for about a foot. In one particular case irregular, black chlorite blebs are seen scattered in a yellowish host rock for several feet.

The effect is quite striking. In common with other types of intrusions, emplacement of intrusives of this type may result in a bleaching of the country rocks for several feet on either side.

All intrusives showed some degree of mineralization. Ilmenite has altered to leucoxene, while pyrite is present as specks and irregular masses but rarely as euhedral crystals.

Veining phenomena appear to be restricted to quartz and mixed quartz-chlorite types. All the dykes of this type are associated with displacements on the strata. Throws of up to 50 feet were noted on such dykes. In this respect they differ from the meladiorites.

Petrography: These rocks were phanero-crystalline, fine-grained with an average grain size of about 0.5 mm. but have now altered to the extent that the majority of constituents are fine-grained secondary minerals. The rock is equigranular and consists of essential plagioclase and pyroxene and possibly amphibole.

The plagioclase occurs in the form of laths, normally stumpy, which are either altered to saussurite or have suffered chloritization. Maximum symmetrical extinction angle obtained was  $19^{\circ}$  but relatively few grains were sufficiently fresh for measurement purposes. This indicates andesine.

The pyroxene has altered to uralite which is found as fibrous aggregates and which has often altered to chlorite. Chlorite is often the most abundant mineral and occurs as small flakes throughout the rock.

Quartz is commonly associated with the chlorite and may be filled with tiny chlorite inclusions. It is also found as clear, fine-grained mosaics in the rock. Epidote is not as common as in the meladiorites but is usually present as tiny grains and granular aggregates which are of a whitish colour in reflected light, perhaps due to their small grain size or to some other property such as alteration.

Calcite occurs in varying amounts in different dykes. It is usually found as irregular grains replacing all other minerals and also appears as small rhombs.

Leucoxene is common but less so than in the meladiorites. Size of the grains is small, while shapes are square or elongated. Recrystallization to sphene has occurred on a reasonable scale.

#### 5. Carbonatite.

##### General.

This is certainly the most striking and interesting rock in Vaal Reefs mine and is described in detail here. The rock is found as a thin dyke trending north-south with local variations in strike. Dip is of the order of  $60^{\circ}$  to the east. Thickness varies between one foot and two feet. The dyke has a 3 foot displacement of the strata on either side.

The rock is very striking due to the amount and variety of xenoliths contained in it (pl XXI). The carbonate matrix is a greyish-brown colour which turns greyish-white after exposure. In hand specimen the dyke material appears to be crystalline. When the dyke was originally intersected a sample was sent to the Anglo American Research Laboratory (A.A.R.L.) for identification. It was identified as a possible dolomite carbonatite (van Zyl, 1963).

##### Petrology

Contact Phenomena : Both contacts are sharp and regular to the naked eye and under the microscope the contact is still seen to be sharp (pl XXII). Due to later movement yellow mylonite has formed along the contact in parts. There is usually a clear distinction between the host rock matrix material and the mylonite although here and there a gradation appears to be present. The host rock is fine-grained with fine yellow speckling due to rutile aggregates. Streakiness in the quartzites is partly due to tiny veins of magnetite, pyrite, leucoxene and limonitic (?) material. The limonitic material has a dirty appearance and is opaque in transmitted light but brownish in reflected light. Irregular patches of matrix replaced by carbonate heighten the streaky appearance. Minerals identified in the country rock are muscovite,



Plate XXI

Handspecimen of the ankeritic beforite showing an abundance and variety of rounded igneous and sedimentary xenoliths. Half natural size.

chlorite, sericite, quartz, leucoxene, pyrite, magnetite, zircon and tourmaline, which showed a secondary overgrowth on an original rounded grain.

No chill zone is present in the dyke although at the contact the rock is very fine-grained for 2 mm. (pl. XXII). Here there is a greater concentration of opaque minerals. Other minerals seen in this narrow zone are biotite, (partly altered to penninite), apatite, amphibole, plagioclase, quartz, chlorite and stilpnomelane as small, rounded grains (0.04 mm.).

Away from the immediate contact, plagioclase laths, almost completely altered to saussurite, occur and the grain size reaches 0.1 mm. and remains constant at this figure. Near the contact apatite grains may reach 0.25mm. There is a definite streaking or flow-banding in the dyke near the contact. This is emphasized by the distribution of iron oxides and pyrite.

#### Mineralogy and Petrography.

These were studied by means of thin sections, polished sections, crushed fragments and heavy residue work. For the purposes of heavy residue work small pieces of rock, visibly free of xenoliths, were selected. These were broken down to  $\frac{1}{4}$  inch, placed in warm 1:5 HCl and occasionally stirred until all reaction had ceased. After filtering, drying and removal of fines by decantation aggregates were broken down by light taps with a pestle. Separation was carried out in bromoform.

The dyke is a hybrid rock, being contaminated by xenoliths of varying size. In order to arrive at an estimate of the specific gravity, the rock was broken up into small pieces and fragments which appeared to be free from xenoliths were used for the determinations. Six determinations were made on a Jolly Spring Balance. The results varied between 2.91 and 2.94 with an average of 2.92.

The dyke is holocrystalline, aphanitic with some larger carbonate grains reflecting light from cleavage faces in hand specimen. The carbonate in thin section is equigranular with an allotriomorphic-granular texture and average grain size of 0.1 mm. The grain size varies

between 0.5 mm. and submicroscopic. No exsolution textures as reported by Russell and others (1954) or Coetzee (1964) were noted. A variety of staining techniques proved unsuccessful in distinguishing the various carbonates. Through other methods the following carbonates were recognised : mesitite, ankerite, magnesite, calcite and ankeritic dolomite. The magnesite was found only as rather large grains which may be xenolithic in character. The colour is pale orange with colour-banding. Ankerite is soluble only in warm dilute HCl. It was found as cream-coloured to pale brown grains, with refractive indices  $n_w$  1.720 and  $n_e$  1.515. Mesitite was found in the undissolved portion after treatment with warm, dilute HCl. It is soluble only in hot, dilute acid. The refractive indices determined are  $n_w$  1.792 to 1.800 and  $n_e$  1.575. The mineral turns brown on heating. Calcite was readily identified by its reaction with cold 1:5 HCl and positive Ca tests. The ankeritic dolomite is described under "Chemistry".

Quartz is next in abundance after the carbonate. It is present as clear grains and also as pinkish-coloured grains. The mode of occurrence is usually as mosaics of tiny grains. The grain size varies from 0.5 mm. downwards.

Stilpnomelane was found to be rather common. Under the binocular microscope it is almost black with a sub-metallic lustre and red internal reflections. Birefringence appears to be high but is masked by the deep colour. The mineral has a small 2V and is optically negative. Perfect cleavage was observed and the refractive indices are  $n_x$  1.740 and  $n_z$  1.635. It occurs as rounded grains and as flakes.

Biotite occurs as larger laths and flakes than stilpnomelane. The biotite has usually altered to magnetite and chlorite; often biotite and magnetite are found interleaved. The variety of chlorite is penninite, readily identifiable by its anomalous interference colours. Quartz occasionally replaces the biotite along cleavage directions.

Amphibole grains are usually slightly larger than the average grain size of the carbonate and are also partly altered to chlorite, and partially replaced by quartz. The minerals recognised are tremolite and hornblende. The tremolite is pale yellow-green, pleochroic from pale green to pale brown. The extinction angle cleavage to  $z = 19^\circ$  and the refractive indices are  $\chi 1.635, \kappa 1.620$ . The hornblende is dark grey-green, pleochroic from dark green to light green with a bluish tint, and has refractive indices  $\chi 1.680$  and  $\kappa 1.660$ . The extinction angle cl. to  $z = 26^\circ$ .

Apatite occurs throughout the rock as euhedral grains which may reach 0.25 mm. in size. Tiny rodlike inclusions in the grains are arranged in a hexagonal pattern.

Sphene and/or perovskite are abundant in the dyke groundmass although their distribution is patchy. They tend to be more concentrated in those parts which show flow-banding. Sphene has a very high birefringence while perovskite is isotropic. However due to the small size of the crystals and internal reflections it was not possible to determine relative percentages. The minerals are often found associated with haematite and irregular sphene may border haematite grains. The minerals appear to be younger than the haematite.

Orthoclase is rather rare and occurs as whitish, cloudy crystals. Likewise plagioclase is uncommon and is usually altered to saussurite. Those grains which had not altered displayed low symmetrical extinction angles.

The dyke shows banding towards the contacts. This banding is darker than the usual colour of the groundmass and granitic fragments and opaque minerals are found in it (pl. XXIII). It is interpreted as being due to flow during emplacement. Such banding has been described by Russell and others (1954) Campbell Smith (1953) and Verwoerd (1963). The most common mineral found in these bands is haematite, usually with a lath-shaped habit (pl. XXIV). It is whitish grey in reflected light and shows beautiful, red internal reflections and strong anisotropism. It is found as a late, irregular mineral along

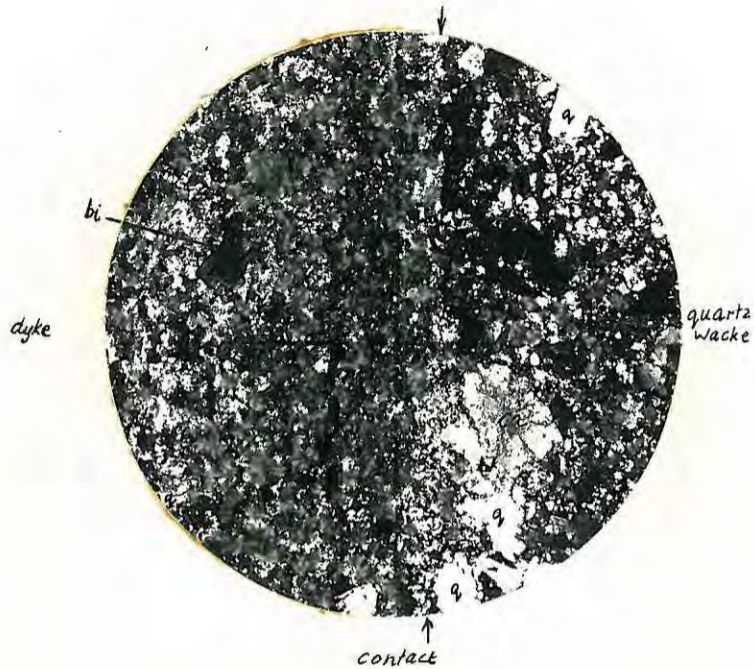


Plate XXII: Contact of ankeritic beforsite against quartz wacke. Note sharp contact, finer grain size of carbonate at contact and carbonate grains in country rock. Quartz (q), carbonate (ca), biotite (bi). Crossed nicols, x 30.



Plate XXIII: Slightly contorted flow-banding in the ankeritic beforsite. Magnetite and haematite (black), carbonate (grey and white). Polarized light, x 32.

carbonate boundaries, as veins and as finely disseminated grains, seen as a red dust between crossed nicols. In the flow-banded zones magnetite is also very common in the form of anhedral grains. They are usually enclosed by haematite, an alteration product (pl. XXIV). The two minerals are readily distinguishable in reflected light.

Pyrite is less common than the above minerals. It occurs in two forms: either as euhedral grains or as irregular masses. It occurs throughout the dyke but is more concentrated in the banded portions where it forms discontinuous streaks parallel to the other mineral banding.

Chalcopyrite is common in the banding where its distribution is patchy. It occurs as porous aggregates between haematite veinlets. Pyrite may be associated. The chalcopyrite appears to be younger than the haematite.

A study of one polished specimen across the banding revealed what appeared to be tiny hackly grains of gold which were bright yellow and had not taken a perfect polish. These grains were found in the porous chalcopyrite-pyrite patches. However, after repolishing the specimen, the grains could not be found again. A gold assay on the remainder of the specimen gave 0.1 dwts per ton.

The paragenesis of the opaque minerals follows the course magnetite (-----> haematite), pyrite, chalcopyrite.

#### Chemistry.

It was felt that a partial chemical analysis of the dyke groundmass would help in the determination of the nature of the carbonate. Small fragments were selected, crushed and thoroughly mixed. About 0.02g was used for the volumetric determination of  $\text{CO}_2$  while 0.5g was used for the determination of  $\text{Al}_2\text{O}_3$ , CaO, MgO, FeO and insolubles. The rock powder was placed in hot 1:5 HCl and the amount of insoluble material was determined after filtering, washing and drying. The results of the analysis are set out on following page :-

Table 16  
Partial chemical analysis of the carbonatite.

Constituents	: composition	%
Insolubles	:	25.00
Al <sub>2</sub> O <sub>3</sub> + X	:	1.61 (X = TiO <sub>2</sub> + P <sub>2</sub> O <sub>5</sub> sol-)
CaO + SrO	:	22.38 (soluble SiO <sub>2</sub> = 0.1% in spectrograph )
MgO	:	12.14
FeO	:	5.69
CO <sub>2</sub>	:	33.33
Total	:	<u>100.15</u>

From this molecular proportions were calculated:

CaO	0.398	
MgO	0.301	
FeO	0.079	CO <sub>2</sub> = 0.757
Total	<u>0.778</u>	

Therefore the ratio CaO : MgO : FeO  
is 5 : 4 : 1

This indicates an iron-bearing or ankeritic dolomite. A trace element study was kindly carried out by the Anglo American Research Laboratory for the author. The sample supplied was analysed qualitatively on a spectrograph.

Table 17

Trace elements in the carbonatite.

Elements	Pb, Cr, V, Cu, Ti (< 0.1%), Ni, Co, Ba (< 0.5%), Sr (< 0.5%), K.
Not detected.	Cd, As, Bi, B, P, Sb, Sn, Nb, W, Ta, Ce, Y, Zr, La, Ag, Zn, Rb (?)

The rubidium determination was inconclusive due to interference of iron.

The most common trace elements usually found in carbonatites are : Ti, Ba, Sr, Nb and Rb. Ti, Ba and Sr were found in this study. Approximate concentrations are shown. Verwoerd (1963) carried out trace element studies of eight South African carbonatites from which he found that relatively high Sr contents characterize all the carbonatites. Rare earths (especially La and Ce) were characteristic of all but two. Elements which were not detected were Pt, Cr, W, Zr, Zn, Cs, Li, U, Ru, Rr, Gd, Tb.

Russell and others (1954) list the trace elements found in the carbonatite at Loolekop and the minerals in which these elements were detected. The most abundant trace elements were Sr, Ba, La and Y. Thus the trace elements listed above suggest that the dyke has carbonatitic affinities.

Xenoliths:

The dyke may be termed a dyke breccia or almost dyke 'conglomerate' as the xenoliths are usually rounded and are abundant in number. They vary in size from less than 1 mm. to over 10 cm. Basic reaction rims are often developed along dyke/xenolith contacts and the boundaries between the xenoliths and the dyke groundmass may be sharp or gradational in different cases. The diffuse contacts are due to tiny fragments breaking off from the xenoliths and becoming incorporated in the groundmass. The rounding of xenoliths is caused by corrosion by the magma.

The majority of the xenoliths consist of granite and often differ widely in appearance, e.g. pale pink, consisting of quartz, pink feldspar, green amphibole and a small amount of chalcopyrite; dark red with accessory pyrite; yellowish with the centre being more siliceous than the periphery, where ferromagnesian minerals are concentrated; pink-coloured, coarse-grained consisting of quartz, albite, orthoclase, hornblende and biotite.

Milky quartz xenoliths are common and are usually smaller than the granite xenoliths. These are probably derived from quartz veins in the original granite or from quartz veins in the quartzites in the Witwatersrand System.

Quartzite xenoliths of four varieties were noted and these are rather common. The types observed were grey, very siliceous; green, siliceous; dark green, medium-grained and dark grey, medium-grained, siliceous.

Chert, although not common, was also found to be present, e.g. black and angular fragments and elongated, khaki-coloured varieties.

Two syenite xenoliths were noted in the samples studied. One was dark-coloured, plutonic, made up of

pink feldspar and dark green ferromagnesian minerals with a dark reaction rim of ferromagnesian minerals surrounding the xenolith. The other xenolith consists of green feldspar with pink patches together with biotite and pink feldspar arranged to impart a somewhat gneissose texture.

Several small possible xenoliths of magnesite were seen, size about 0.5 mm. They may be original constituents of the dyke groundmass, being locally coarse-grained but they are well-rounded and may be xenoliths too.

Several xenoliths of amphibolite were found which were well-rounded and are of a dark green colour. They are composed of hornblende and quartz.

Xenoliths of gneiss were usually composed of the minerals of granite, concentrated into bands of feldspar and ferromagnesian minerals alternating with quartz, although several had a dioritic composition.

A single xenoliths of shale was recorded. This is rather hard, and dark in colour with distinct bedding.

A striking xenolith of jaspilite was observed. The rock is very angular, fine-grained and hard. Alternating layers of black magnetite and red jasper give rise to a banded effect.

In addition, two xenoliths, whose identity is unknown, were noted. One, a very fine-grained, black ferromagnesian rich rock, possibly basalt, and the other very fine-grained, rather dark red, resembling a felsite.

#### Other Occurrences.

Two other occurrences, rather similar in hand specimen to the above dyke (with the exception of the xenoliths), were encountered in the mine. One of these revealed dyke-like form on 65 Level, No.1 Shaft where it is found against a quartz diabase dyke and the other was seen in the core of borehole V7 where it has been logged as a dyke breccia.

The dyke on 65 Level is only a few inches wide. It is bordered on the eastern side by a northwest trending quartz diabase dyke and on the western side it is in sharp contact with Vaal Reef Zone quartz wackes.

A thin section shows that only 50 per cent of the rock is made up of carbonate, probably calcite, which replaces all other minerals. Its grain size reaches 0.3 mm. It seems that the original rock was normal quartz wacke, which has suffered replacement by the carbonate which has come from the now highly altered quartz diorite. A qualitative spectrographic analysis of this rock was carried out by A.A.R.L. for the author:

Table 18

Major constituent	: Si.
Minor constituents	: Cr, Ca, V, Cu, Ti (< 0.1%), Ni, Mn.
Very faint	: Na, Pb, Co, Ba.
Not detected	: Cd, As, Be, B, P, Sb, Sn, Nb, W, : Ta, Bi, Ce, Y, Zr, La, Ag, Sr, Zn, : K, Rb.

Borehole V7 is situated in the southwestern corner of the mine. The length of "dyke" intersected was 12 feet but the angle of dip is not known. This occurrence is also in contact with quartz wacke on one side and dyke on the other. In hand specimen the rock is a grey colour with a greenish tint. The rock is sheared with bands of mylonite being developed in it. Under the microscope the rock is a quartz wacke largely replaced by carbonate whose grain size may reach 0.75 mm.

A.A.R.L. performed a qualitative spectrographic analysis on a sample of this rock, Table 19.

Table 19

Major constituents	: Fe, Si.
Minor constituents	: Ms, Al, Mn, Ni, Cr.
Traces	: Sn, Ca, V, Cu, Na, Ti (< 0.1%) : K, Co, Zn.
Very faint	: As, Pb, Ba, Sr.
Not detected	: Cd, Bi, B, P, Sb, Nb, W, Ta, Ce, : Y, Zr, La, Ag, Rb.

Origin of the Carbonatite.

The dyke at first glance resembles a fault breccia. It cannot, however, be a fault breccia because the xenoliths are so varied and rounded and the throw is very small.

Two modes of formation may be considered:

- 1.) Intrusion,
- 2.) Replacement of an original basic intrusive.

1.) The rock occurs in the form of a thin dyke and contains rounded xenoliths. This suggests intrusion. The mineralogy of the dyke is similar to that of many carbonatites which have been described. Such minerals as biotite, apatite, sphene, magnetite, haematite, pyrite, chalcopyrite and alkali feldspar have been described from carbonatites by Turner and Verhooggen (1960), Verwoerd (1963), Daly (1925), Russell and others (1954), Campbell Smith (1953), Pecora (1956) and Johnson (1961).

The evidence of the mineralogy is supported by the trace-element study which showed Sr, Ti, Ba and Rb(?). These are characteristic of carbonatites.

Streaking or flow-banding, such as seen in the dyke, has been described by various authors and magnetite and apatite are usually found in such banding, (Pecora, 1956; Johnson, 1961; Campbell Smith, 1953 and Verwoerd, 1963). This is in all likelihood due to liquid injection.

The contacts are finer grained for a very short distance and this probably represents a chill zone. Chill zones in carbonatites have rarely been described in the literature.

The variety of carbonates present suggests an origin by intrusion rather than replacement. Since emplacement the rock has suffered some movement as seen by shearing in the quartzites and mylonite.

2.) In favour of an origin by replacement is the fact that several dolerite dykes, which contain a great variety and abundance of xenoliths, occur between Klerksdorp and Ventersdorp (Nel, 1935). Nel terms them "hybrid rocks". His description, especially that of the xenoliths, suggests a correlation between these dykes and in Vaal Reefs. However, the groundmass shows no textural similarity at all.

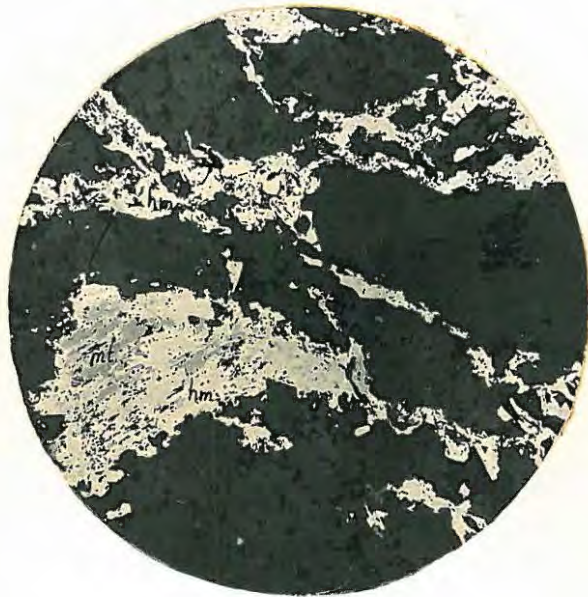


Plate XXIV: Haematite banding in ankeritic beforosite. The haematite (hm) is an alteration product of magnetite (mt). Polished section, x 92.

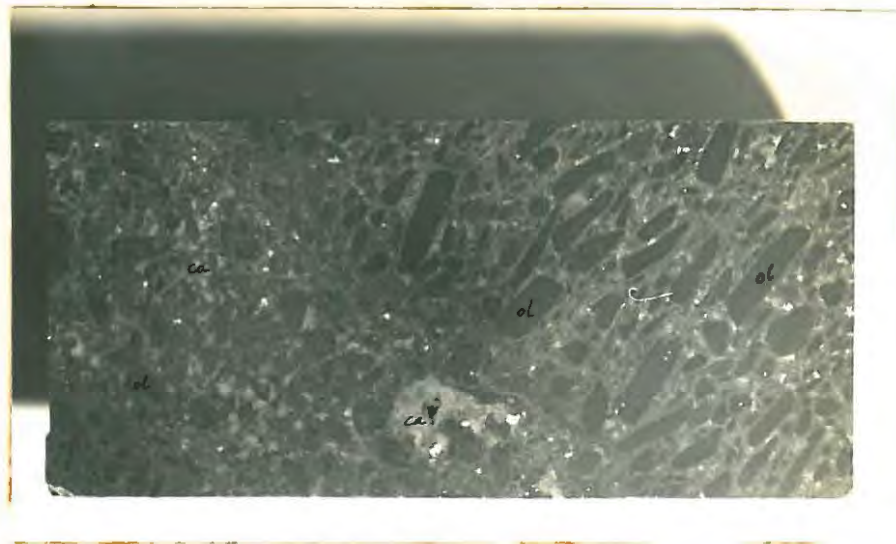


Plate XXV: Handspecimen, olivine lamprophyre. The corroded olivine phenocrysts display parallelism. Olivine (ol), carbonate (ca). x 1.5.

Nel mentions carbonate as being secondary and of very minor importance.

The thin dyke-like body on 65 Level and the rock intersected in V7 bear a superficial resemblance to the carbonatite in hand specimen. They must have formed by replacement of the country rock. The carbonate was probably derived from the contiguous dykes which are themselves much altered. In thin section these rocks show no resemblance to the carbonatite and are probably not related.

The evidence therefore suggests that the dyke formed by liquid injection, probably a magma. The xenoliths were taken up from underlying Basement rocks and possibly Dominion Reef System. It is possible that there are several such bodies in the area and that a larger source may lie under cover of younger rocks or at a greater depths.

The carbonatite may be termed an ankeritic beforosite.

#### 6. Olivine Lamprophyre.

Up to the time of writing this dyke has not been intersected in Vaal Reefs workings. It is found in the neighbouring mine, Western Reefs, and crosses the boundary into Vaal Reefs near the southwest corner of the mine. The dyke is the youngest igneous rock in the area and cuts through all other structures without being affected. The strike is wonderfully constant at  $N4^{\circ}E$  to  $N1^{\circ}E$  while dip is either  $90^{\circ}$  or very close to this figure.

The dyke is thin, usually 4 feet thick, reaching 10 feet. A number of unpleasant features are associated with this intrusive as far as mining is concerned, e.g. it is water bearing, it is highly sheared and tends to collapse thus necessitating sealing with concrete. Horizontal slickensiding is common along the contacts, the striations being filled by fibrous carbonate.

The dyke is striking in hand specimen. It has the appearance of a breccia with ovoid and elongated black inclusions, length up to 1 cm, set in a dark grey

groundmass (pl. XXV). These "inclusions" are in fact phenocrysts. They are oriented sub-parallel to one another and this together with the variation of colour in the groundmass indicates flow. The phenocrysts are not developed within 9 inches of the contacts, which are a dark greenish-grey to black colour.

The rock has a smooth, rather greasy feel which is due to talc and serpentine. The phenocrysts are not uniformly distributed throughout the dyke, some parts containing an abundance of these while other parts are relatively unaffected. Mica is distinctly visible both as pale flakes and as red specks which resemble garnets at first glance.

Petrography :

Several thin sections of the dyke and its contacts were cut. The rock is strongly porphyritic. Under the microscope the rather dark green to black phenocrysts are seen to be olivine pseudomorphs while less conspicuous phenocrysts of biotite are very common. These are set in a fine grained groundmass. The rock is holocrystalline and shows a hypidiomorphic-granular texture which was probably panidiomorphic before alteration affected the constituents. The panidiomorphic-granular texture is characteristic of lamprophyres. The phenocrysts may be single or occur as very loose glomeroplastic aggregates.

The olivine phenocrysts reach 10 mm. in length and are elongate oval in thin section. Corroded margins are common, sometimes resulting in angular shapes. Original olivine is rarely present in the cores of phenocrysts, the mineral having been replaced by either carbonate (probably magnesite or ankerite Hatch et al, 1952) or serpentine. Expansion cracks are ubiquitous and magnetite may be abundant in these (pl. XXVI). The serpentine has rather a high birefringence, about 0.01. Talc is also found as a constituent of the pseudomorphs. These olivine phenocrysts are earlier than the biotite phenocrysts as seen by some biotite surrounding olivine.

Biotite occurs as corroded and altered euhedral phenocrysts. The mineral tends to be rather bleached



Plate XXVI. Olivine lamprophyre. Corroded olivine phenocrysts, now altered to magnetite (black) and serpentine, in a groundmass of carbonate and chlorite. Shreds of biotite (bi) barely visible. Crossed nicols, x 29.

and both bleached interiors with dark borders and dark interiors <sup>with</sup> bleached borders were noticed. The bleached biotite is a pale green to pale brown colour. A certain amount of alteration to chlorite has taken place. The unaffected grains show strong pleochroism from dark brown to pale brown. Unaltered biotite is often observed adjacent to completely pseudomorphed olivine.

Alteration of the biotite gives rise to the red spots seen in hand specimen. This is limonite. Basal sections of the altered biotite show rutile needles arranged in three sets at  $60^{\circ}$ , apparently due to titanio acid released from the biotite (Harker 1960). Secondary minerals like quartz and carbonate are found as lenticular bodies along the cleavage planes of the biotite. The biotite phenocrysts are occasionally bent and they, like the olivine, may be found singly or in clusters.

The groundmass consists of secondary minerals, viz. saussurite, chlorite and calcite. The saussurite is an alteration product of plagioclase, none of which remains. The composition of plagioclase in such lamprophyres is generally near that of andesine (Hatch et al, 1952)

The carbonate is very abundant and replaces most other minerals. Its grain size varies from 1.5 mm. downwards and it is usually present as fine grained aggregates.

Any original augite or amphibole has been completely altered to chlorite, a common constituent of the groundmass.

All other minerals are less common. Tiny octahedra of magnetite are scattered throughout the groundmass. In some thin sections sphene (or perovskite) is very abundant as wedge-shaped and irregular grains. Perovskite is known as a common accessory in such rocks. Pyrite is found as irregular grains, usually larger in size than the magnetite grains. One possible grain of stilpnomelane was encountered which has a torpedo shape and dark brown colour, being surrounded by a reaction rim of dirty carbonate. Apatite is seen in very small amount as prismatic grains and as delicate needles.

At the contacts chlorite is more common. It replaces the matrix of the country rocks and also attacks the quartz grains, forming spherulitic embayments.

A rather peculiar pink colour is developed in the sedimentary rocks at the contact. A thin section failed to reveal the reason, unless the quartz itself is a pink colour. The colour may possibly be due to a dissemination of very fine limonitic material. Lamprophyres are generally named by the predominant mafic material present and the nature of feldspar. Thus this dyke is an olivine lamprophyre. The author has not encountered any reference to olivine lamprophyres in the literature however. As the original feldspar was a plagioclase the rock may also be termed an olivine kersantite.

#### The Alteration of the Intrusives.

The intrusives in the mine are almost invariably highly altered and the contacts are generally more highly altered than the centres.

The minerals of the rocks are stable in conditions of low-grade regional metamorphism, the greenschist facies.

The question arises as to whether such alteration is due to metamorphism or deuteric alteration and the views of various authors differ on this point.

The production of saussurite, an aggregate of albite, zoisite, calcite, sericite and other Ca - Al silicates could be due to retrogressive metamorphism according to Ramberg (1952). Wahlstrom (1950) on the other hand suggests a deuteric origin but states this is generally due to "dislocation and hydrothermal alteration by extraneous solutions". Harker (1956) gives both points of view e.g. p. 174-5, "The observations of numerous petrologists indeed lead to the conclusion that saussuritization and uralitization alike belong to a late stage in the cooling down of an igneous rock. Shearing stress, if it operates, is doubtless to be reckoned as a factor favouring these changes". On p. 352, he mentions the extreme slowness of cooling in the final stages of regional metamorphism allowing, "spontaneous reactions to proceed more freely". Thus, "the saussurite change gives rise to, instead of an obscure cloudiness, distinct crystals of zoisite or epidote". Tyrrell (1956) states that the anorthite molecule is unstable under conditions of dynamic metamorphism

and breaks up into saussurite.

Therefore, while saussurite can form both from deuteric effects and from metamorphism, the body of opinion appears to favour metamorphism in one form or another.

The original pyroxene is no longer present in the dykes while uralite is found only in the diorites where it alters to chlorite. Tyrrell (1956) and Harker (1956) show that uralite forms under conditions of thermal metamorphism or dynamothermal metamorphism while Hatch and others (1952) state that late stage alteration can change pyroxene to fibrous uralite. Metamorphism which caused any such change was probably more thermal than dynamothermal as relict igneous textures are still seen in the rocks.

The alteration of pyroxene to chlorite frequently gives rise to calcite and quartz as by-products. Tyrrell (1956) states that any ferromagnesian mineral may break down into chlorite at an early stage of metamorphism while Wahlstrom (1950) prefers an origin through late stage processes of a deuteric nature.

With respect to the opaque minerals, Harker (1956) feels that leucoxene is formed at the expense of titaniferous iron ore as a result of dynamic metamorphism. Tyrrell (1956) mentions conditions of dynamothermal metamorphism for its formation, "Under dynamothermal metamorphism. . . leucoxene, a dense aggregate of minute granules of sphene, arises from alteration of ilmenite, and under more intense metamorphism large crystals of sphene are formed from ilmenite or other titaniferous minerals." The author has not found any references to support a deuteric origin for leucoxene.

Quartz occurs, both as a result of alteration of other minerals and as introduced veins, which may be very abundant. While some of these veins may be late stage, others have filled later fractures. The quartz has effected silicification of the older dykes. Pyrite has both crystallized as a deuteric mineral and been introduced by later hydrothermal solutions. Calcite is present as a result of alteration of primary minerals but has also been introduced by later solutions and is usually the

youngest mineral present.

The views presented and the evidence of the dykes themselves suggest that both deuteritic phenomena and regional metamorphism have played parts in the alteration of the primary minerals, together with later modifications through hydrothermal solutions. Several mineral changes suggest that regional metamorphism has played the greater role.

Such is not the case with the lamprophyre which, being very young, has not shared in the metamorphic episodes. Alteration here is due to deuteritic phenomena. Analyses of lamprophyres show large amounts of  $\text{CO}_2$ ,  $\text{H}_2\text{O}$  and  $\text{H}_2\text{S}$  which cause alterations of minerals in these rocks. Examples of the deuteritic effects are bleached biotite, the carbonates and pseudomorphs of talc and serpentine after olivine.

#### Age Relationships.

The lamprophyre is the youngest intrusive as it is not affected by any structural feature. Antrobus (1956) has described an augite lamprophyre from the Orange Free State Goldfields which has been found to be post-Karoo, and probably late Cretaceous in age and it is felt that the olivine-lamprophyre was intruded at much the same time.

The carbonatite on the other hand is affected by faulting, both big and small, and so is older. At present its exact age is not determinable. Verwoerd (1963) has tabulated the ages of South African carbonatites as extending from post-Transvaal to Cretaceous and Recent. No other occurrences have been described in the vicinity so that no comparisons can be made. Its age is possibly post-Transvaal.

With respect to the other dykes no occurrences of these dykes in Transvaal system rocks have been encountered either in Vaal Reefs or the neighbouring Western Reefs mine. Borehole cores of Transvaal System rocks are not retained after drilling so that samples of any post-Transvaal intrusives in the nearby vicinity are unobtainable.

The oldest dykes appear to be the quartz diabases. Of these the porphyritic, non-porphyritic and feathery varieties are probably of much the same age. The

amygdaloidal diabase shows much alteration too and many similarities to the quartz diabases but has suffered less subsequent movement and is probably slightly younger.

These dykes are moved by later faulting which is pre-Transvaal and probably also pre-Upper Ventersdorp in age.

These dykes therefore are probably feeders of the lavas. The amygdaloidal type suggests an affinity with the lavas.

The microdiorites are probably largely contemporaneous. They show less disturbance than the quartz diabases and are thought to be younger than the latter. However conclusive intersections have not yet been observed. The meladiorites appear to be similar to the ilmonite-diabases described by Brandt (1949), Ellis (1946), Antrobus (1956) which are thought to be pre-Transvaal by these authors. Thus the meladiorites may also be pre-Transvaal.

A table of possible ages is presented below.

Table 20.

Type	Age
Quartz Diabases	Lower Ventersdorp.
Amygdaloidal Diabase	Lower or Upper Ventersdorp.
Mela- and Mottled Microdiorites	Post- Ventersdorp
Carbonatite	Post- Transvaal
Lamprophyre	Post- Karroo.

It is likely too that the intrusives of any one type were not intruded at any one time but over an extended period of time.

CHAPTER 4THE VENTERSDORP SYSTEM.

The Ventersdorp System on the Vaal Reefs property consists of the Ventersdorp Contact Reef overlain by a considerable thickness of lavas.

The V.C.R. has been intersected in several boreholes. Its best development is in the No. 3 Shaft area where it is 9 feet thick, consisting of mixed, medium-sized pebbles and carrying sporadic gold value. No mining has been done on this horizon in the Vaal Reefs Mine.

The Ventersdorp lavas may reach a thickness exceeding 3,800 feet (in borehole Z3 on the northern boundary) but the thickness is generally less than this on account of faulting and erosion.

According to Nel (1939) the Ventersdorp lavas are ". . . greenish or bluish-grey, aphanitic rocks of andesitic composition."

Whyte (1952) first pointed out that there appeared to be an unconformity between the lower and the upper portions of the lava in the Western Reefs Mine. His evidence was ". . . the consistent relative position of certain markers in the lava to its base and of others to the base of the Transvaal System." Winter (1965) has worked on the lavas in the Bothaville area and confirmed that regional unconformities do exist in the Ventersdorp System. A study of his isopach maps reveals that either his Lower or Upper and perhaps both divisions could be present in the Vaal Reefs Mine, his Middle division being absent.

The Lower, or Langgeleven Formation is certainly present while the Upper division, represented by the Allanridge Formation, appears to be present in some of the boreholes and not in others. The following Formations are thus not represented; the new Kameeldoorns, Makwassie, Rietgat, and Bothaville.

The Langgeleven Formation.

The Langgeleven Formation consists of andesites, both amygdaloidal and non-amygdaloidal, of a rather pale grey-green colour. It has proved possible to subdivide

this Formation according to various marker horizons.

a. Large phenocryst zone : This is a zone of amygdaloidal and non-amygdaloidal lavas immediately overlying the Elsburg Stage reaching a maximum of about 100 feet above the base of the Formation. The zone is occasionally not seen in borehole cores. The phenocrysts are scattered and may reach  $1\frac{1}{2}$  inches in size. Towards the base the phenocrysts are a very dark green colour due to complete chloritization of original feldspar crystals. Upwards the phenocrysts gradually lighten in colour to white and at the same time become smaller in size. No specimens were fresh enough for investigation of their optical properties. Nel (1939) has reported that the composition is similar to that of albite. Winter (1965) states that the lowermost 200 feet of the Langgeleven formation consists of talcose tuffs but in Vaal Reefs cores tuffaceous layers were found to be thin and not restricted to any particular horizon.

b. Finely-porphyrific zone : Some distance above the Large Phenocryst zone ( up to a maximum of 900 feet above the base) there is a zone of finely-porphyrific, amygdaloidal lava, the phenocrysts being less than one-tenth of an inch in size. They are feldspar crystals and are pale yellow to white in colour. The thickness of the zone may reach 400 feet.

c. Purple Marker zones : There are two recognized Marker zones, which are fairly reliable, the Lower zone being better developed than the Upper zone. The Lower Purple zone is found some 700 feet above the base of the lava and when well developed it is conspicuous. Generally it consists of dense lava with purple-coloured bands containing tiny chlorite amygdales invariably surrounded by alteration haloes. The Upper Purple zone is poorly developed on Vaal Reefs but is similar in character to the Lower zone. Whyte (1952) states that the Upper Purple zone is found 1400 feet above the lava base. The peculiar colour may be due to certain weathering effects on the lava.

d. Linked amygdale zone : Work to the south-west of the Klerksdorp goldfields indicates that a zone of fairly small linked, milky quartz amygdales developed in thin

bands may provide a useful marker horizon. Re-logging of the Vaal Reefs boreholes shows that this is a very poorly developed zone and that its position varies. It may, in fact, occur immediately above the Purple Marker zone.

e. Zone of green chalcedony amygdales : This zone is very occasionally developed and is not a reliable marker; often these green amygdales have elongated "almond" shapes.

f. Altered zones and dense lavas : Winter (1965) states that the variolitic bands and altered zones occurring in the Bothaville area may prove of great use in regional correlation -- " a further hunt for altered zones in the Klerksdorp goldfield, immediately to the north of the map, might yield useful stratigraphic data."

Zones of amygdales with alteration haloes are present in borehole cores and occasionally variolites are well developed. Further work on these is being carried out at present to determine whether the variolitic zones are of correlative value. Alteration haloes surrounding amygdales are common throughout the succession and do not constitute reliable markers.

Attempts to correlate individual flows in different boreholes have been unsuccessful, as have attempts to correlate zones containing chlorite amygdales only. Nonetheless there is a tendency for the lava to be very fine grained and dense towards the top with a very poor development of amygdales.

Contrary to Winter's statement concerning the area to the south there are virtually no agglomerates in the Langgeleven formation in the Vaal Reefs cores, so that one cannot use the presence of these to delineate the top of the formation.

#### The Allanridge Formation.

The Allanridge Formation consists of green to dark green andesitic lavas, the top portions of flows being highly amygdaloidal. The amygdales are very much larger than in the underlying Langgeleven formation. They consist of large, irregular quartz and chalcedony types together with rounded chlorite bodies. Some of the amygdales are pink in colour and this often helps to distinguish

these lavas from the Langgeleven formation. In addition the non-amygdaloidal middle portions of flows are more coarsely crystalline than in the Langgeleven, and are often finely-porphyrific in character.

The Allanridge formation constitutes some of the Ventersdorp System on Vaal Reefs but it is thin and may prove to be absent from some of the holes. It is proving extremely difficult to find the dividing-line between the Allanridge and Langgeleven formations as no convenient sediments or agglomerates are present. The major faulting is pre-Transvaal in age (possibly pre-Allanridge) and this has resulted in greater thicknesses of lava being preserved in down-faulted blocks e.g. in the north and north-east the lava reaches more than 3800 feet, while in the unfaulted block south of No. 3 Shaft the lava is less than 2000 feet thick.

To the west of Vaal Reefs the lava overlies the Witwatersrand System unconformably but this unconformity gradually fades towards the basin centre. Because of the variation of heights of various marker beds above the base, the lava still lies unconformably on the underlying rocks on Vaal Reefs Mine. It appears to be conformable with the Transvaal System above and intercalations of lava and sediments (quartzites and dolomites) are relatively common at the top. Nel's map of the Klerksdorp-Potchefstroom area (1939) shows that the Ventersdorp and Transvaal Systems are conformable near the Vredefort Dome.

CHAPTER 5THE TRANSVAAL SYSTEM

The Transvaal System is represented by the Black Reef and Dolomite Series. The cores of all boreholes drilled through these formations on the property have been discarded so that the author has had to rely on the logs of boreholes for much of the information.

Black Reef Series.

This Series is best developed in borehole M5 where it is 60 feet thick. In borehole V2 the Series is not developed at all and in several boreholes an alternation of dolomite and quartzite comprises the base of the System.

The Black Reef Series consists of black, probably carbonaceous shales and bluish-grey to light-grey, medium to coarse-grained quartzite which is often gritty and which contains lenticular, small-pebble conglomerates and a fair amount of pyrite. The shales and quartzites do tend to have a tuffaceous appearance which is not surprising as the Transvaal System sediments contain the interbedded lavas near the base. The percentage of quartzite in the Black Reef Series varies from 7 per cent to 100 per cent, but is generally less than 50 per cent the remainder being shale. This is in contrast to the character of the Series in the outcrop area to the west on Western Reefs where it is composed mainly of quartzites and conglomerates. Thus there is a change to a more argillaceous facies away from the outcrop. It is fairly certain that the original limit of the Black Reef was not much further west than its present position.

The conglomerates which are present are developed at the base and were deposited in hollows in the original surface so that many of the Vaal Reefs boreholes did not intersect conglomerates.

The Series can be divided into Lower, Middle and Upper portions (Fig.20). The Lower portion consists of quartzite up to 25 feet thick, overlain by a carbonaceous shale which may reach 15 feet in thickness. The Middle portion again consists of quartzite (up to 14 feet) and

black shale ( up to 16 feet). The Upper portion consists of thinner intercalations of quartzite and black shale.

#### The Dolomite Series

This Series underlies the entire surface of the mining lease area. The dip is towards the basin centre at a rather low angle and as the topography falls off towards the Vaal River only a limited section of the series is exposed at surface. The series reaches a thickness of more than 2000 feet in the south-east. Near the base there are many black shale bands which tend to decrease in number and thickness upwards, usually within 60 feet of the base. The lower portion of the Series tends to be darker grey than the upper portion which has been logged as "grey to white, banded dolomites" (Fig.21). Exceptions are numerous e.g. M8 has been logged as light-coloured dolomite throughout while V7 contains all dark dolomite. An important point to bear in mind is that operator variance could account for much of the inconsistency. It is accordingly suggested that not much importance should be attached to the colour.

Thin bands of black shale are numerous throughout the succession and are usually less than 6 inches thick. Thin layers of chert are also present but are rarely found in the lower portion.

The Series has been described as consisting of dolomites and dolomitic limestones but it is not possible to determine the mineralogy by optical means in thin section. Under the microscope the rocks consist of coarse to fine-grained, anhedral and subhedral grains of carbonate with small amounts of quartz and argillaceous material. Occasionally iron staining along grain contacts gives evidence of the presence of siderite.

The Black Reef and Dolomite Series have suffered hardly any faulting but a fair amount of slumping of the dolomite must have occurred as shown by contorted bedding in borehole cores. The Kromdraai fault which displaces the Vaal Reef up to 2500 feet has had a small amount of post-Transvaal movement and the fault outcrop can be traced on the surface. The effect of the faults on iso-

pachs of the Transvaal System can be seen in Fig.22.

The author has not encountered any stromatolitic structures on Vaal Reefs but has found a boulder of float on the neighbouring Western Reefs property which has stromatolitic features.

CHAPTER 6THE STRUCTURE OF THE VAAL REEFS MINE.

" The greater portion of the area underlain by the Vaal Reef forms an elliptical basin with a northeast to southwest axis of elongation. This direction is roughly parallel to the axis of the regional Transvaal syncline shown on sheet 61 of the Geological Survey. This elliptical basin is bounded by the Kromdraai fault in the southeast and the Buffelsdoorn fault in the northwest". ( Wilson and others, 1964).

The structural plan accompanying this chapter (Fig.23 ) shows Vaal Reef contours, faults and dykes cutting the reef. All elevations are relative to a datum 6000 feet above sea level. The deepest reef mined to date is -8200 feet while the shallowest is - 6000 feet. Figs. 24 and 25 show various sections across the mine.

The strike of the Vaal Reef varies in different fault blocks but generally remains close to northeast-southwest. This is parallel to the basin edge in this area. Over most of the mined-out area the dip is towards the northwest. Nearer the suboutcrop position, e.g. in Western Reef Mine, the dip is towards the southeast. In the vicinity of No. 2 Shaft the axis of a shallow anticline trends northeast (parallel to the basin edge) so that to the southeast of this the beds continue to dip towards the centre of the main Witwatersrand syncline. Due to this anticline and the low inclination of the beds in the vicinity of No. 2 shaft dips and strikes are more variable than in the rest of the mine.

1. Unconformities and Disconformities:

There are several unconformities and disconformities present in the stratigraphic section. The Vaal Reef lies disconformably upon the MB5 zone of the Livingstone Stage, cutting down through these beds in a northwesterly direction. The Kimberley Stage of the Kimberley-Elsburg Series lies disconformably upon the rocks of the Main-Bird Series such that the Upper Vaal Zone thins from 150 feet in the southeast to nothing in the northwest portion of the mine. This disconformity becomes a pronounced unconformity on the Klerksdorp Townlands, several miles

to the West (Nel, 1939).

There is an unconformity between the rocks of the Witwatersrand System and those of the overlying Ventersdorp System which increases to the northwest but dies out towards the centre of the Witwatersrand basin. Although it is difficult to prove this from borehole information alone in Vaal Reefs, there is evidently a regional unconformity between the Lower and Upper Ventersdorp rocks (Whyte, 1952; Winter, 1966; McKinney and others 1964).

Between the Ventersdorp and Transvaal Systems there does not appear to be an unconformity. On the contrary, in several boreholes intercalations of lava and sediments are present at the top of the Ventersdorp System, suggesting more or less continuous deposition.

## 2. Folding:

Generally folding is of minor importance and is hardly noticeable except in the vicinity of the big faulting where it is seen as drag. Most of the folding encountered has been caused by faulting. Rotation in the fault plane is usually involved.

## 3. Faulting:

The structural picture of the mine has been greatly complicated by faulting. As the analysis of the faulting is a study on its own, only a general picture is presented here.

The great majority of faults are normal, indicating that the crust was under tension during the time of faulting. The faulting is a result partly of sedimentation of Witwatersrand beds and partly of the eruption of the Ventersdorp lavas.

There are several types of faults present.

### a. Normal faults parallel to the basin edge:

As mentioned above most of the faulting is normal. The biggest faults on the mine are all normal faults and strike almost parallel to the edge of the basin. The largest of these is the Kromdraai fault which strikes northeast. This is actually a zone of faults with a combined downthrow to the northwest of 2500 feet near the Eastern boundary. It was probably active in pre-Vaal Reef times and movement has taken place at various times. This fault can actually be traced on the surface for many miles.

The displacement in the Black Reef and Dolomite Series is very much less than in the Witwatersrand rocks.

In addition to the Kromdraai fault there are several other normal faults with similar trends and large throws, e.g. between No. 3 Shaft and No. 1 Shaft there is a fault with 600 to 900 feet of throw.

Downthrows on the faults running parallel to the basin edge may be to the northwest or the southeast. The faults generally have dips of the order of  $45^{\circ}$  to  $65^{\circ}$ . A combination of borehole and underground data shows that the dips become less with increasing depth. In fact the Kromdraai fault appears to be nearly vertical on surface. There are innumerable normal faults running parallel to the main faults, often splitting off from them. Both sympathetic and antithetic faulting is present. The faults are usually curved in plan. Together with this type may be grouped the rotational faults which are also normal faults but these are dealt with in a separate section.

b. Normal faults oblique to the basin edge:

These faults are generally steeper and are slightly later than the faulting parallel to the basin edge. They are a readjustment of faulted blocks and tend to block off on the major faults. Very often these faults follow the dyke margins. Throw along these faults often varies considerably due to the blocking off effect and also to the tilting of blocks during adjustment.

c. Reverse Faults:

Although relatively uncommon these faults are encountered. For the most part they have steep dips and small throws. The faults are rarely consistent for large distances and often occur along quartz diabase dykes. Flat-dipping reverse faults (thrust faults) are very uncommon.

d. Rotational faults:

Most of these are strike faults with variable dip. Downthrow is not necessarily restricted to any particular side of the fault. These faults cause inconvenience as throw can vary considerably over short distances, often making it difficult to predict the structure e.g. one particular normal fault with 75 feet throw at one point becomes a reverse fault with

50 feet throw at another point less than 2000 feet away. Faults like this are probably also due to adjustment of earlier faulted blocks. Like the normal faults they are curved in plan. They also show a tendency to block off on other faults - usually against oblique faults along dykes.

c. Tear faults:

There is evidence of tear faulting in Vaal Reefs from displacements of older dykes but the amount of movement is usually less than 50 feet. However, near No. 2 Shaft there is a tear fault running approximately parallel to the Kromdraai fault which shifts two quartz diabase dykes up to 200 feet. Horizontal slickensiding is usually seen in the fault planes.

f. Bedding plane faults:

Often movement has taken place along bedding planes and occasionally normal faults flatten considerably to become bedding-plane faults. Usually such faults are later than all other faults and displace them. There is a considerable amount of bedding-plane faulting in the Argillaceous zone as seen by the development of mylonite but the amount of movement along these planes is not known.

It is often difficult to judge the throw of a fault by its appearance underground; while many of the faults have fault fillings of quartz and pyrophyllite (soapy feel), the bigger faults usually have mylonite along the fault planes. This material is pale green to green or blue in colour and has tiny rounded quartz grains set in a streaky very fine-grained matrix. The substance is pulverized rock which has solidified, the rounded grains not having been crushed. The flow texture is often very striking. Often too, veins of mylonite traverse the surrounding country rock. Some large normal faults may have up to 2 feet of mylonite while others have hardly any at all.

4. Structural history:

The structural history may be summarised as follows:

1. Deposition of Witwatersrand System rocks with intermittent periods of still-stand allowing reworking of Vaal Reef, Denny's Reef etc. and minor

faulting before each stillstand period (pre-Vaal Reef faults have been observed.)

2. A certain amount of faulting and erosion.
  3. Intrusion of dykes and extrusion of lower Ventersdorp lavas.
  4. Development of the large scale, normal basin edge faulting.
  5. Adjustment of fault blocks along oblique faults and planation of the lower Ventersdorp lavas.
  6. Extrusion of more lava accompanied by further faulting which largely ceased in pre-Transvaal times ( except Kromdraai fault).
  7. Deposition of Transvaal System.
  8. Erosion and deposition of younger rocks (c.g. Karroo system) which have subsequently been removed by erosion.
-

### CONCLUSIONS

The portion of the Witwatersrand System described here includes part of the Main-Bird Series and the Kimberley - Elsburg Series. Most of the rocks of the Main-Bird Series are indurated sandstones (quartz wackes) together with conglomerates, an argillite and several bands of orthoquartzite. They consist of quartz and chert grains in a sericitic to partly siliceous matrix, which may constitute over 50 per cent of the rock but is usually near 20 per cent. The rocks vary between medium and coarse-grained and appear to have a shallow water origin in a continental basin as outlined by Brock and Pretorius (1964).

The quartz wackes of the Kimberley-Elsburg are coarser-grained and tend to be "cleaner", approaching quartzose sandstones in their composition. The only mineral found in the Main-Bird Series which was not found in the Kimberley-Elsburg Series is chloritoid and this may prove to be a useful index mineral. The quartz grains have a slightly higher sphericity in the Kimberley-Elsburg Series, probably indicating that the grains were derived from the underlying Witwatersrand rocks. Usually about 80 per cent of the quartz grains are single crystals and this together with features like strain effects and inclusions implies derivation from granites, granite gneisses and veins according to the genetic classification of Folk (1965). The heavy minerals are mostly derived from acid source rocks but several species e.g. chloritoid, some tourmaline and rutile have formed authigenically in the sediments so that a detailed study of heavy mineral distributions should include only definite detrital minerals like zircon, chromite etc.

The Vaal Reef is a very persistent, thin, small-pobble conglomerate which may have formed from both fluvial and beach processes but only a detailed sedimentological study could elucidate this. The value plan (Fig.11) shows a north-south trend of payshoots parallel to the expected current directions (Antrobus, personal communication; Brock and Pretorius (1964, Pl: VI). The mid-lines of payshoots, when joined up, form a braided

pattern much like that of streams on a deltaic plain. The payshoots are areas of greater reworking.

Generally, higher gold value in the reef is associated with larger pebble size. The relative proportions of quartz, quartzite and chert pebbles vary but little over the mine and are not related to gold distribution. The  $U_3O_8/Au$  ratio in the reef can be used in the evaluation of borehole results where core recovery is only partial and contoured ratio maps could prove useful in conjunction with value plans in the prediction of ore reserves.

Gold fineness is considered to be a reflection of the fineness in the original source rocks and the pattern of fineness in the reef can be explained by sedimentary concentration processes.

Although Karroo dolerites have not yet been found in the mine, six different types of intrusives have been established. The oldest of these are the quartz diabase (whereof there are three varieties) and amygdaloidal diabase. The melamicrodiorites and mottled microdiorites are younger and less affected by faulting. The ankeritic beforosite is interpreted as being an intrusive carbonatitic rock and not a replacement rock. Its age is very uncertain but it is probably post-Transvaal. The youngest igneous rock in the mine is the olivine kersantite which is not affected by any other feature. Except for these latter dykes the intense alteration which the intrusives have undergone is due more to metamorphic effects than to deuteric alteration.

The major faulting running more or less parallel to the basin edge in this area developed during Ventersdorp times and movement had ceased before deposition of Transvaal System sediments except for the Kromdraai fault which has a small amount of post-Transvaal movement and which can be traced on the surface. The faults trending in other directions are largely due to later adjustment of fault blocks. The gentle folding observed has been caused by faulting.

ACKNOWLEDGEMENTS.

I am indebted to Professor E.D. Mountain for his assistance and criticisms during the course of this investigation and for the offer of a temporary lectureship during a six month stay at the University.

Considerable valuable advice on the photomicrography and the preparation of polished sections was given by Dr. H.V. Eales and this help is gratefully acknowledged.

I thank the Managements of Angle American Corporation and Vaal Reef Mining and Exploration Company, and in particular Dr. H.C.M. Whiteside, Consulting Geologist, for permission to present this thesis.

Thanks are due to Mr. P.D. Millar, Resident Geologist of the Vaal Reefs Mine for information and facilities provided and to Mr. P.M. Strydom for stimulating discussions and advice.

REFERENCES.

- AMERICAN COMMISSION ON STRATIGRAPHIC NOMENCLATURE. (1961) Code of Stratigraphic Nomenclature. Bull. Am. Assoc. Petrol. Geologists, 45.
- ANTROBUS, E.S.A. (1956) Notes on the Intrusives of the Orange Free State Goldfields. Unpub. Company Report, Anglo American Corp.
- (1956) The Origin of the Auriferous Reefs of the Witwatersrand System. Trans. geol. Soc.S.Afr., 59.
- BAINES, V. (1949) The Geology of the Odonsdaalsrus Goldfield in relation to that of the Klerksdorp District and Notes on the Correlation of the Upper Division of the Witwatersrand System. Trans.geol.Soc.S.Afr., 52.
- BEEZ, P.F.W. (1936) Contributions to the Geology of the Klerksdorp District from the Results of the Drilling Activities by the Western Reefs Exploration and Development Company. Trans.geol.Soc.S. Afr., 39.
- BORCHERS, R. (1964) Exploration of the Witwatersrand System and its extensions, in S.H.Haughton, ed., "The Geology of some Ore Deposits in Southern Africa, Vol.1, Geol. Soc.S.Afr.
- BRANDT, R.T. (1950) The Geology of Certain Igneous Intrusive Rocks in the Far East Rand, Transvaal, South Africa. Unpub. M.Sc. Thesis, Univ. Witwatersrand.
- BROCK, B.B. & (1964) PRETORIUS, D.A. Rand Basin Sedimentation and Tectonics, in Haughton, S.H.ed., "The Geology of some Ore Deposits in Southern Africa", Vol.1. Geol. Soc. S. Afr.

- CAMPBELL SMITH, W. (1953) Carbonatites of the Chilwa Series of Southern Nyasaland. Bull.Brit.Mus. v.1, 4.
- CARTWRIGHT, A.P. (1962) The Goldminers. Furnell & Sons., Johannesburg.
- COETZEE, C.B. (1960) The Geology of the Orange Free State Goldfield. Mem.geol.Surv.S.Afr ., 49.
- COETZEE, F. (1962) Die Verspreiding en Korrelgrootte van Goud, Piriet en Ander Swaar Minerale in Sommige Goudriwwe van die Witwatersrandbekken. Unpub. M.Sc.Thesis.Univ. Orange Free State.
- COETZEE, G.L. (1964) The Sangu Carbonatite Complex Trans.geol.Soc.S. Afr. 67.
- COLLENDER, D.F. (1960) The Witwatersrand System in the Klerksdorp Area as Revealed by Diamond Drilling. Trans. geol. Soc. S.Afr.63.
- CONOLLY, J.R. (1965) The Occurrence of Polycrystallinity and Undulatory Extinction in Quartz in Sandstones. J. Sediment. Pet., 35 No.1.
- DALY, R.A. (1925) Carbonatite Dykes of the Premier Diamond Mine, Transvaal. J.Geol., 33, No. 7.
- DAVIDSON, C.F. (1957) On the Occurrence of Uranium in Ancient Conglomerates. Econ. Geol., 52.
- DEINNY, G.A. (1897) The Klerksdorp Goldfields. London.
- DE JAGER, F.S.J. (1964) The Witwatersrand System in the Springs-Nigel-Heidelberg Section of the East Rand Basin, in Haughton, S.H. ed., "The Geology of Some Ore Deposits in Southern Africa,"Vol.1, Geol.Soc.S. Afr.
- DE KOCK, W.P. (1964) The Geology & Significance of the West Wits. Line, in Haughton, S.H.ed., "The geology of some Ore Deposits in Southern Africa, vol. 1, Geol.Soc.S.Afr.

- DROSDOFF, M. and (1935) A Method for Removing Iron  
TRUOG, E. Oxide Coatings from Minerals.  
Amer.Miner.,V.20.
- DRYDEN, A.L. (1931) Accuracy in Percentago Repres-  
entation of Heavy Mineral  
Frequencies.  
Proc. nat.Acad.Sci., 17.
- EALLES, H.V. (1960) Gold Fineness in Hydrother-  
mal Ores.  
Unpub.Ph.D.Thesis,Rhodes Univ.  
----- (1965) Polarization Figures as an  
Aid to Identification of  
Polished Isotropic Minerals.  
Am.Miner., 50.
- EDWARDS, A.B. (1960) Textures of the Ore Minerals  
and their Significance.  
Austr.Inst.Min.Met.,Melbourne.
- ELLIS, J. (1940) An Intrusion of Quartz Doler-  
ite occurring in the Far East  
Rand.  
----- (1944) Trans.geol.Soc.S.Afr. 43.  
Further examples of Subterranean  
Subsidence of the Marie-  
vale Type and Syntexis Assoc-  
iated with them.  
----- (1946) Trans.geol.Soc.S.Afr., 47.  
The Simple Dykes and Sills of  
the Far East Rand.  
----- (1947) Trans.geol.Soc.S. Afr., 49.  
The Marievale Granophyre, a  
Metamorphic Rock.  
Trans. geol.Soc. S.Afr.,50.
- FISHER, M.S. (1939) Notes on the Gold,Pyrito and  
Carbon in the Bankets.  
Bull.Inst.Min.and Metall.,  
London, No.414.
- FOLK, R.L. (1965) Petrology of the Sedimentary  
Rocks. Homphills, Austin,  
Texas.
- FULLER, A.O. (1958) A Contribution to the Petro-  
logy of the Witwatersrand  
System.  
Trans.geol.Soc.S.Afr.,61.
- HARGRAVES, R.E. (1961) Silver Content of Gold in  
Witwatersrand Conglomerates.  
Inf.Circ.Econ.Geol.Res.Unit,  
Univ. Witwatersrand No.3.

- HARKER, A. (1956) Metamorphism.  
Methuen Dutton.
- (1960) Petrology for Students.  
8th ed. Cambridge Univ. Press.
- HATCH, F.H. (1952) Petrology of the Igneous Rocks.  
WELLS, A.K. AND Murby.  
WELLS, H.K.
- JOHNSON, R.L. (1961) The Geology of the Dorowa and  
Shawa Carbonatite Complexes,  
Southern Rhodesia.  
Trans. geol. Soc. S. Afr., 64.
- KOEN, G.M. (1955) Heavy Minerals as an Aid to  
the Correlation of Sediments  
in the Northern part of the  
Union of South Africa.  
Trans. geol. Soc. S. Afr., 58.
- (1961) The Genetic Significance of  
the Size Distribution of  
Uraninite in Witwatersrand  
Bankets.  
Trans. geol. Soc. S. Afr., 64.
- KRUMBEIN, W.C. AND (1938) Manual of Petrography.  
PETTLJOHN, F.J. Appleton.
- & SLOSS (1963) Stratigraphy and Sedimentation.  
2nd ed., Freeman. California.
- LAWN, J.G. (1924) Presidential Address on  
Subject of Silver in Witwater-  
strand Ores.  
Proc. geol. Soc. S. Afr., 27.
- LIEBENBERG, W.R. (1955) The Occurrence and Origin of  
Gold and Radioactive Minerals  
in the Witwatersrand System,  
the Dominion Reef, the Venter-  
sdorp Contact Reef and the  
Black Reef.  
Trans. geol. Soc. S. Afr., 58.
- MALAN, S.P. (1959) The Petrology and Mineralogy  
of the Rocks of the Dominion  
Reef System near Klerksdorp.  
Unpub. M.Sc. Thesis, Univ.  
Witwatersrand.
- McKINNEY et al (1964) Geology of the Anglo American  
Group Mines in the Welkom  
Area, Orange Free State Gold-  
field, in Haughton, S.H. ed.,  
"Geology of Some Ore Deposits  
in Southern Africa." V.1 Geol.  
Soc. S. Afr.

- MILNER, H.B. (1962) Sedimentary Petrography Vol.1  
4th ed. Allen and Unwin.
- MOORHOUSE, W.W. (1959) The Study of Rocks in Thin  
Section.  
Harper and Brothers, New York.
- NEL, L.T. (1935) The Geology of the Klerksdorp-  
Ventersdorp Area.  
Expl. Geol. Map No. 37, Spec.  
Pub. geol. Surv. S. Afr., 9.
- (1939) The Geology of the Country  
around Potchefstroom and  
Klerksdorp.  
Expl. Geol. Map No. 61, Geol.  
Surv. S. Afr.
- (1958) The Occurrence of Uranium in  
the Union of South Africa.  
Proc. 2nd U.N. Int. Conf.  
Peaceful Uses of Atomic Energy,  
2.
- (1960) The Genetic Problem of Uran-  
inite in the South African  
Gold-bearing Conglomerates.  
Rep. Int. Geol. Cong. Sess. No. 21,  
part 15.
- PACKHAM, G.H. (1955) Volume, Weight, and Number-  
frequency of Sediments from  
Thin Section data.  
J. Geol., 63.
- PECORA, W.T. (1956) Carbonatites: A Review.  
Bull. geol. Soc. Amer., 67.
- PETTIJOHN, F.J. (1957) Sedimentary Rocks.  
2nd ed. Harper, New York.
- PIROW, H. (1920) Distribution of Pebbles in  
the Rand Banket and other  
features of the Rock.  
Trans. geol. Soc. S. Afr., 23.
- PRENTICE, T.K. (1940) Precious Metal Constituents of  
Witwatersrand Ores.  
Annual Proc. Assoc. sci. Tech.  
Soc. S. A. Afr.
- RAMBERG, H. (1952) Origin of Metamorphic and Met-  
asomatic Rocks.  
Univ. Chicago press.
- RAMDOHR, P. (1958) New Observations on the Ores  
of the Witwatersrand in  
South Africa.  
Trans. geol. Soc. S. Afr. Annex.  
to Vol. 61.
- REINECKE, L. (1927) The Location of Payable Ore-  
bodies in the Gold-bearing  
Reefs of the Witwatersrand.  
Trans. geol. Soc. S. Afr., 30

- RICHARDS, G.P. AND RUBIDGE, E.A.D. (1950) Estimation of Silver in Gold Ores. S.Afr. Ind. Chem., 4.
- RUSSELL, H.D. (1954) The Mineralogy and Petrology of the Carbonatite at Loolekop, Eastern Transvaal. Trans.geol.Soc.S.Afr., 57.
- SANDERS, J.E. and KRAVITZ, J.H. (1964) Mounting and Polishing Mineral Grains on a Microscopic Slide for Study with Reflected and Polarised light. Econ. Geol., 59.
- SCHLEE, J. (1957) Upland Gravels of Southern Maryland. Bull. geol.Soc.Amer., 68.
- SIMPSON, D.S. (1952) Correlation by means of Radioactive Logging in the Witwatersrand System in the Klerksdorp Area. Trans.geol.Soc.S.Afr., 55.
- SKOLNICK, H. (1965) The Quartzite Problem. J.sediment.Pet., 35, No.1.
- SNYMAN, C.P. (1965) Possible Biogenetic Structures in Witwatersrand Thucholite. (Abstract) In press.
- STEYN, L.S. (1963) The Sedimentology and Gold Distribution Pattern of the Livingstone Reefs in the West Rand. Unpub. M.Sc.Thesis Univ. Witwatersrand.
- STRYDOM, P.M. (1959) Supplement to the Geological Section of the Western Transvaal Goldfield. (Revised notes Geol.Cong.)
- TURNER, F.J. and VERHOOGEN, J. (1960) Igneous and Metamorphic Petrology. 2nd ed. McGraw-Hill.
- TWENHOFEL, W.H. and TYLER, S.A. (1941) Methods of Study of Sediments. McGraw-Hill, New York.
- TYRRELL, G.W. (1956) The Principles of Petrology. Methuen, London.
- VAN ANDEL, T. (1959) Reflections on the Interpretations of Heavy Mineral Analyses. J.sediment. Pet., 29.

- VAN DER PLAS, L. (1962) Preliminary Note on the Granulometric Analysis of Sedimentary Rocks. Sedimentology, v.1.
- VAN NIEKERK, C.B. (1959) A Petrographical Study of Certain Dykes of Pilansberg Age, Intrusive into the Witwatersrand System. Unpub. M.Sc. Thesis, Univ. Pretoria.
- VANZYL, C. (1963) Unpublished Report. Anglo American Research Laboratory.
- VERWOERD, W.J. (1963) South African Carbonatites and their Probable Mode of Origin. Unpub. D.Sc. Thesis, Univ. Stellenbosch.
- VILJOEN, R.P. (1963) Petrographic and Mineralogical Aspects of the Main Reef and Main Reef Leader of the Main-Bird Series. Witwatersrand System. Unpub. M.Sc. Thesis, Univ. Witwatersrand.
- VON RAHDEN, H.V.R. (1965) Apparent fineness values of gold from two Witwatersrand Gold Mines. Econ. Geol., 60.
- WAHLSTROM, E.E. (1950) Theoretical Igneous Petrology. John Wiley and Sons, New York.
- (1958) Igneous Minerals and Rocks. John Wiley and Sons, New York.
- WARDAUGH, T.G. (1960) A Comparative Petrological Study of some Sedimentary Rocks from South Africa and the Surrounding Continents and the Significance of their Heavy Mineral Contents. Unpub. M.Sc., Thesis, Univ. O.F.S.
- WHITESIDE, H.C.M. (1944) Heavy Mineral Analyses of Two Reefs from the Far East Rand. Unpub. M.Sc. Thesis, Univ. Witwatersrand.
- WHYTE, W.J. (1952) The Geology of Western Reefs Exploration and Development Company. Unpub. Company Report, Anglo American Corporation.

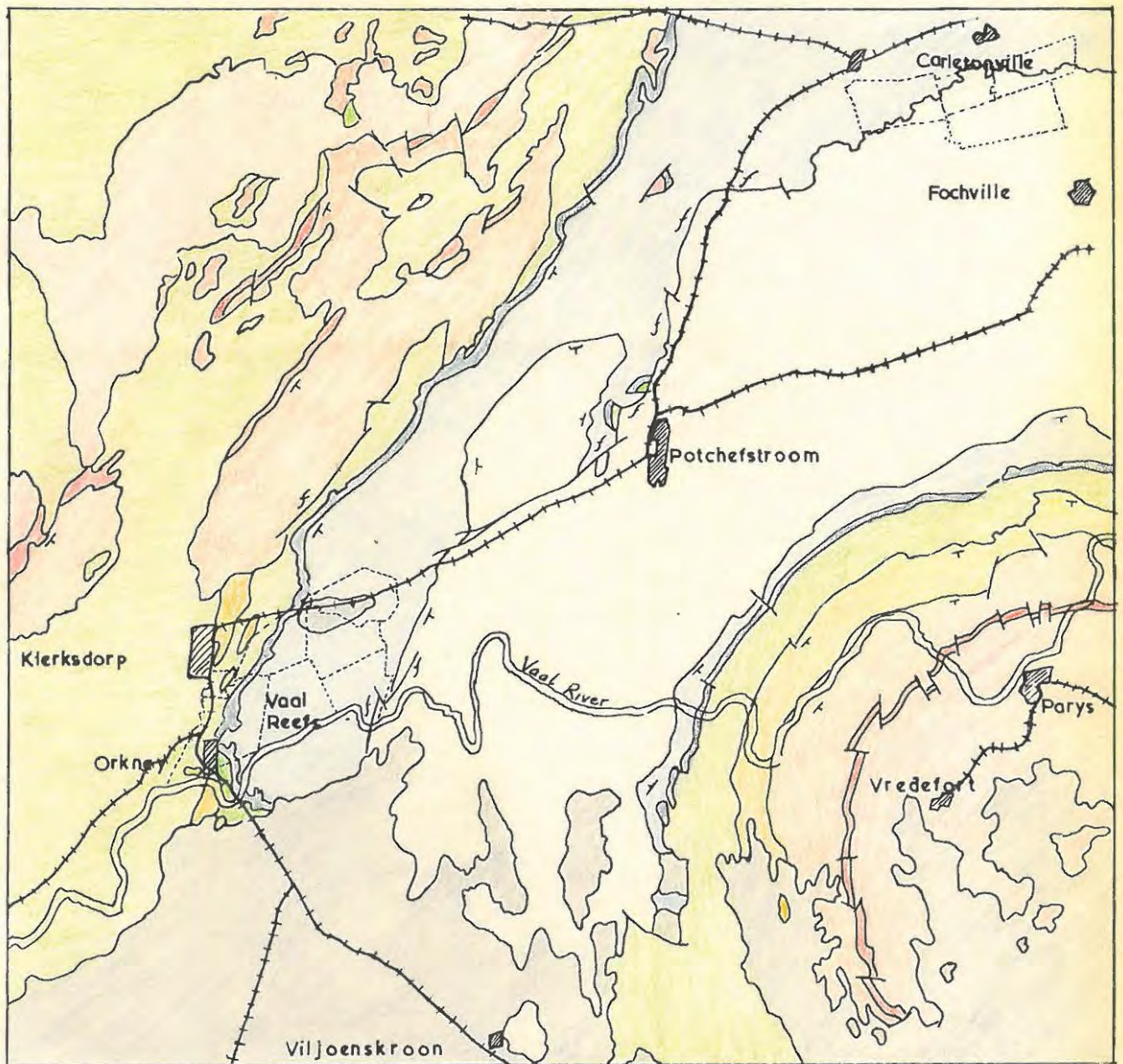
- WILLIAMS, H. (1958) Petrography.  
TURNER, F.J. AND W.H. Freeman and Company.  
GILBERT, C.M.
- WILSON, N.L. (1964) The Geology of the Vaal Roof  
OOSTHUIZEN, D.H. Basin in the Klerksdorp Area  
BRINK, W.C.J. and in Haughton, S.H. ed. "Geology  
TOENS, P.D. of Some Ore Deposits in  
Southern Africa", vol. 1.  
Geol.Soc.S.Afr.
- WINTER, H.DE LA R. (1957) The Upper Division of the  
Witwatersrand System in the  
Virginia and Morrispruit  
Mining Areas.  
Unpub. M.Sc. Thesis, Univ.  
Pretoria.
- (1965) The Stratigraphy of the  
Ventersdorp System in the  
Bothaville District and  
Adjoining Area.  
Unpub.Ph.D.Thesis, Univ.  
Witwatersrand.
- YOUNG, R.B. (1917) The Banket of the South  
African Goldfields.  
Gurney and Jackson, London.

**LOCALITY PLAN AND GENERALIZED  
GEOLOGICAL MAP OF PORTION OF  
THE WITWATERSRAND BASIN.**


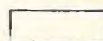






(after Borchers).






Scale 1:600,000.



**LEGEND**

- |   |                      |                        |
|---|----------------------|------------------------|
|  | Karoo System         |                        |
|  | Pretoria Series      | ] Transvaal System     |
|  | Dolomite Series      |                        |
|  | Black Reef Series    |                        |
|  | Ventersdorp System   | ] Witwatersrand System |
|  | Upper Division       |                        |
|  | Lower Division       |                        |
|  | Dominion Reef System |                        |
|  | Basement Formations  |                        |

-  Mining Properties
-  Faults
-  Strike and dip

**FIG. 1.**

— KLERKSDORP GOLDFIELDS —  
PLAN OF MINING PROPERTIES  
AND  
BOREHOLE LOCATION PLAN FOR VAAL REEFS

Scale 1:100,000

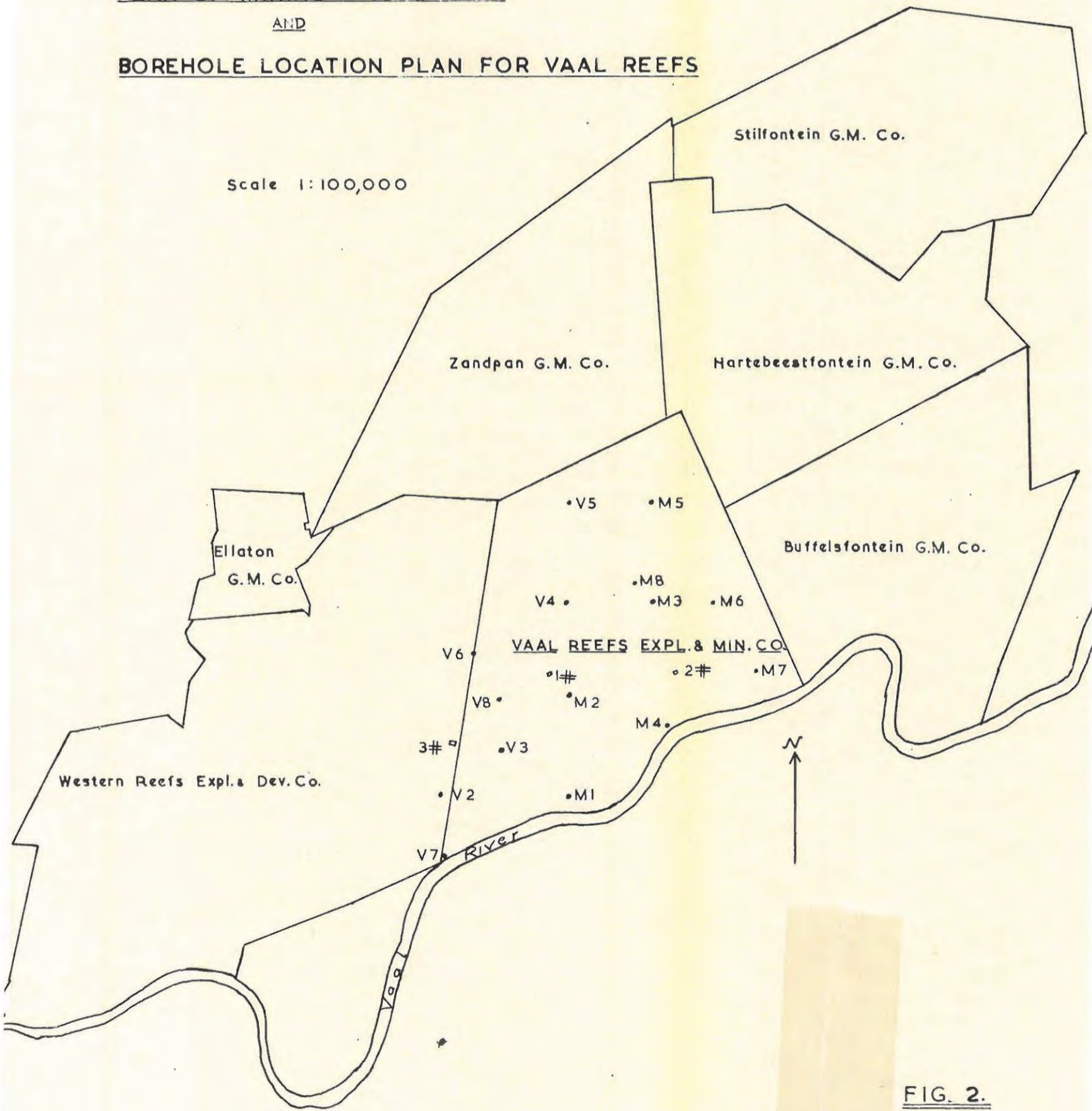
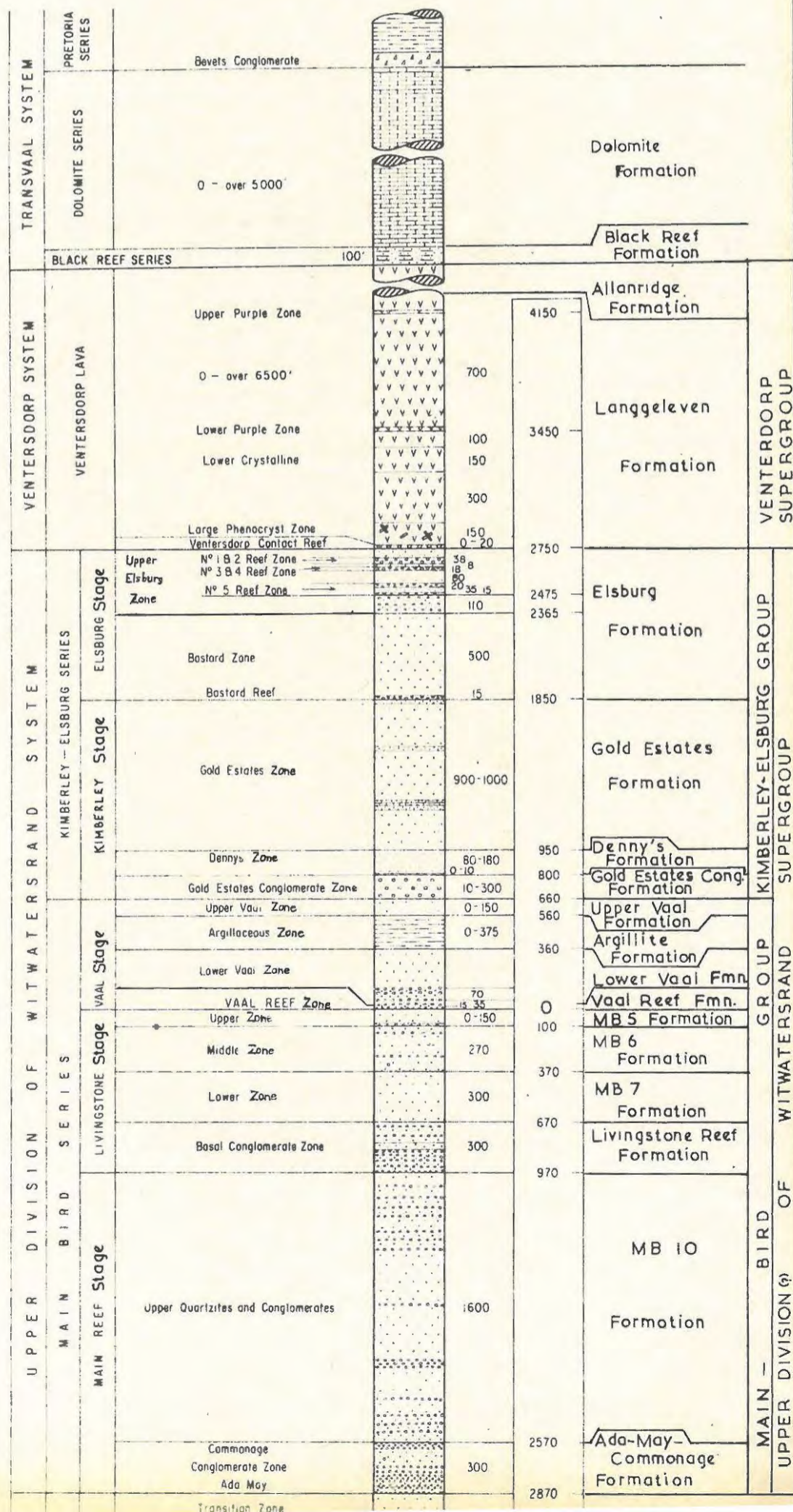


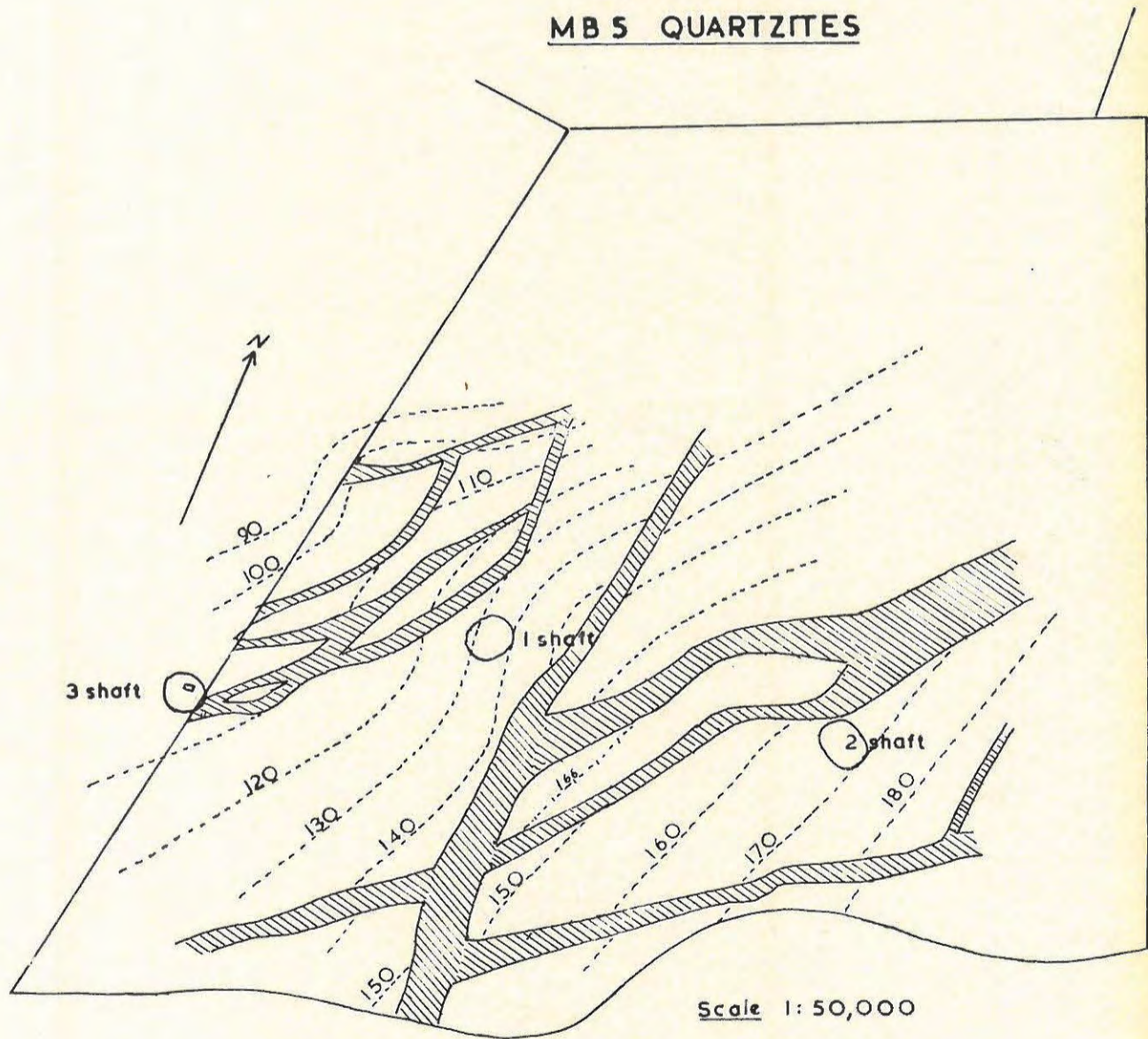
FIG. 2.

FIG. 3.

GENERALISED GEOLOGICAL SECTION  
OF WESTERN TRANSCAAL GOLDFIELDS  
SCALE 1:10,000



ISOPACH MAP  
MB 5 QUARTZITES



Contour interval 10 feet


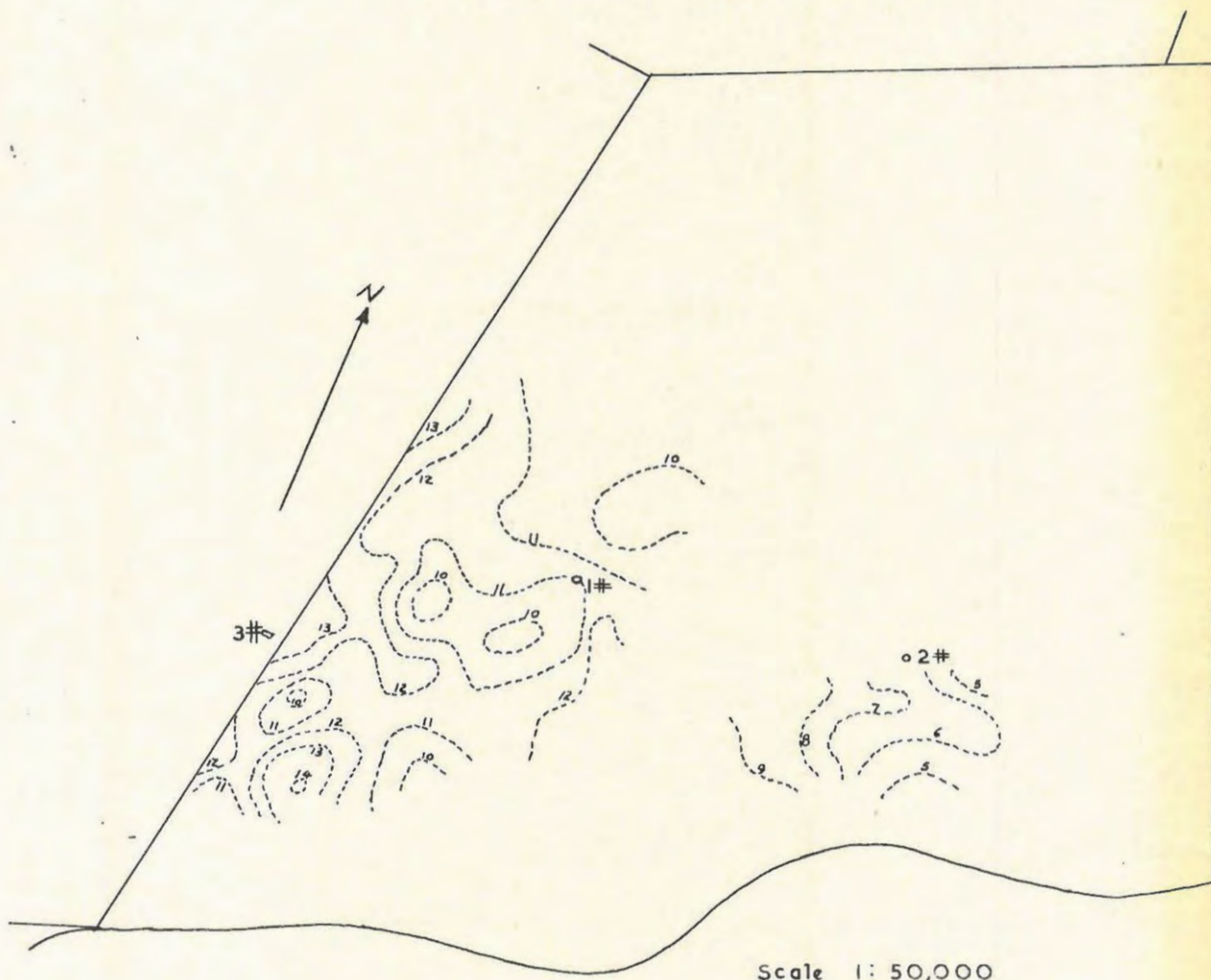
 fault losses

FIG. 4.

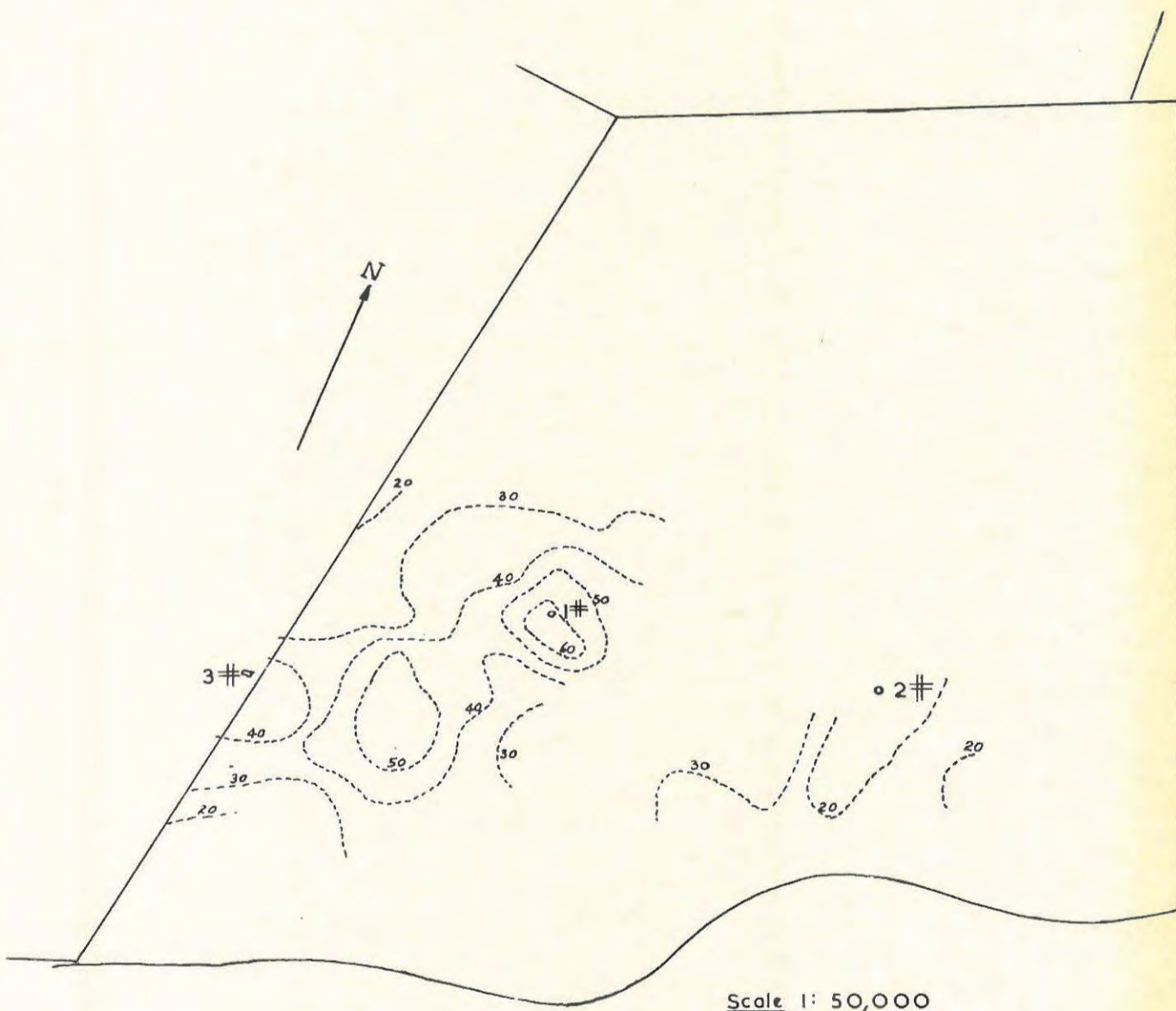
ISOPACH MAP  
of  
THE ORTHOQUARTZITE BETWEEN THE  
VAALE REEF AND 12 FT. MARKER



Contour interval 1 foot: Based on moving average values

FIG. 5.

ISOPACH MAP  
OF  
12 FT. MARKER.

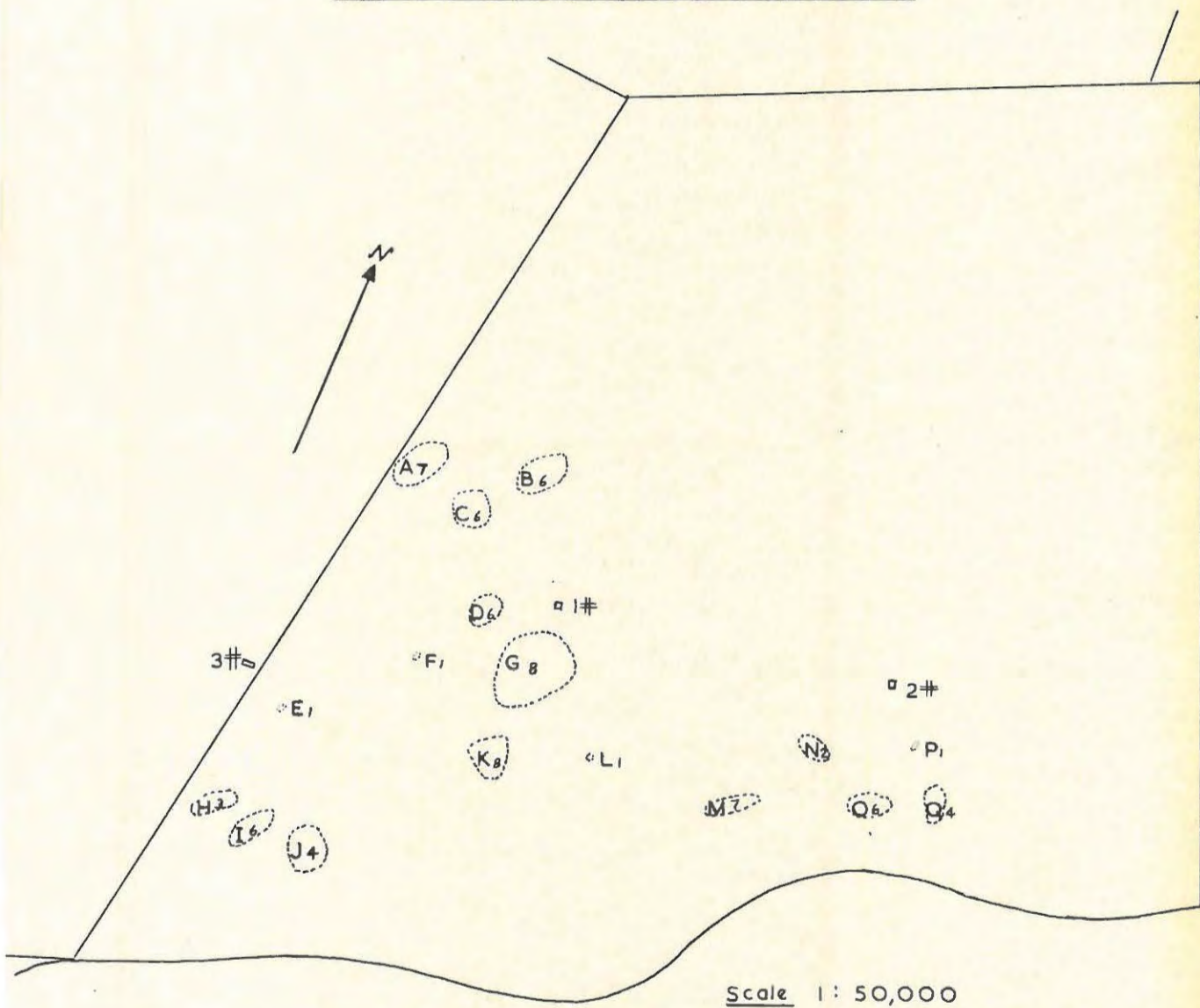


Contour interval 10 inches.

Drawn from moving average values

FIG. 6.

PLAN SHOWING AREAS SAMPLED  
 FOR MAXIMUM PEBBLE SIZE  
 AND PEBBLE-TYPE PERCENTAGES.



KEY

- boundary of area sampled
- G index letter for particular area (see tables I and II)
- 6 number of observations

FIG. 7.

SIZE DISTRIBUTION CURVES.

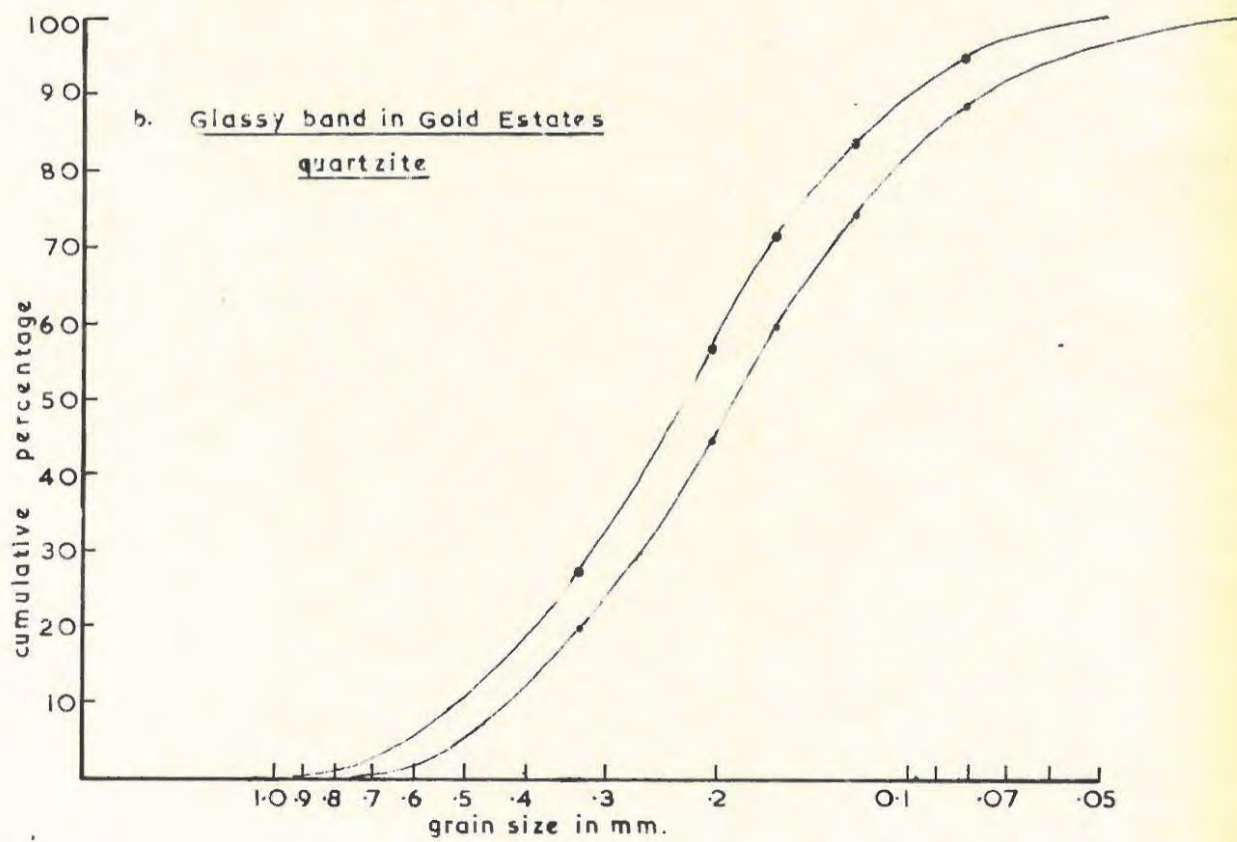
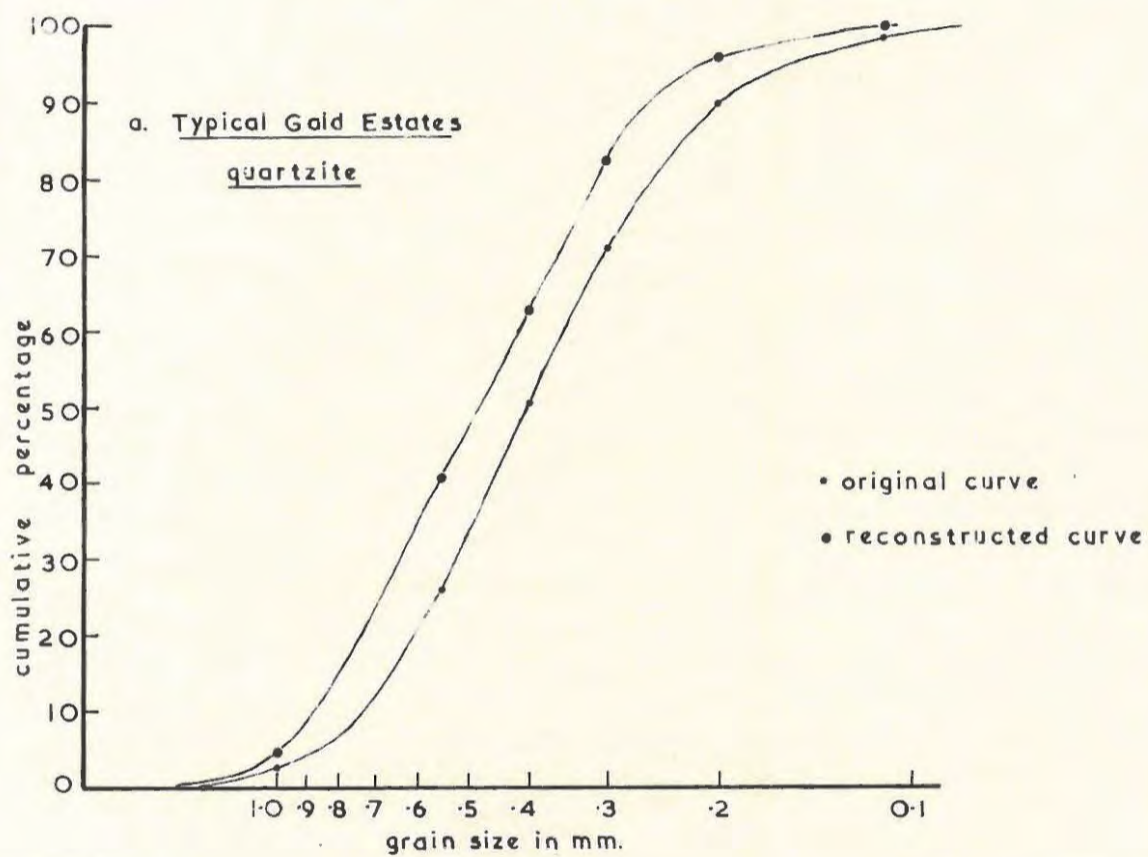
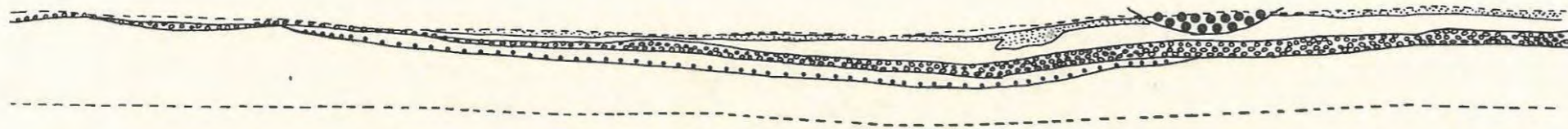


FIG. 8.



SECTION 2/54 42 A RAISE

SCALE - 1:200

- ..... Preserved remnant of 'older' Vaal Reef.
- ~~~~~ Vaal Reef disconformably overlying the older Vaal Reef.
- ~~~~~ Pyritic grit.
- Erosion channel filled with hangingwall marker conglomerate.
- Hangingwall and footwall of Raise.

FIG. 9.

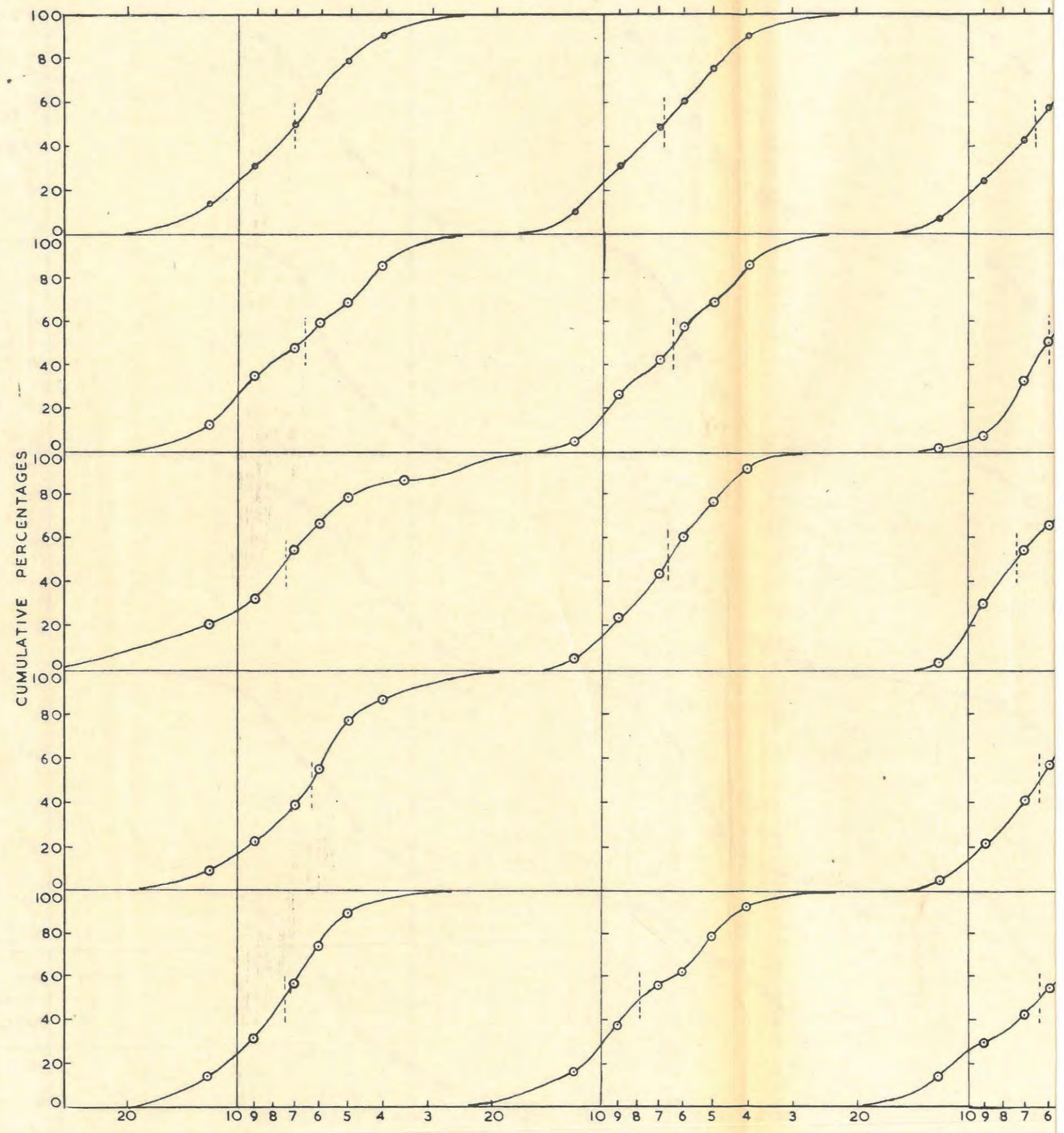
sample no. 551

346

REF  
(of ob by

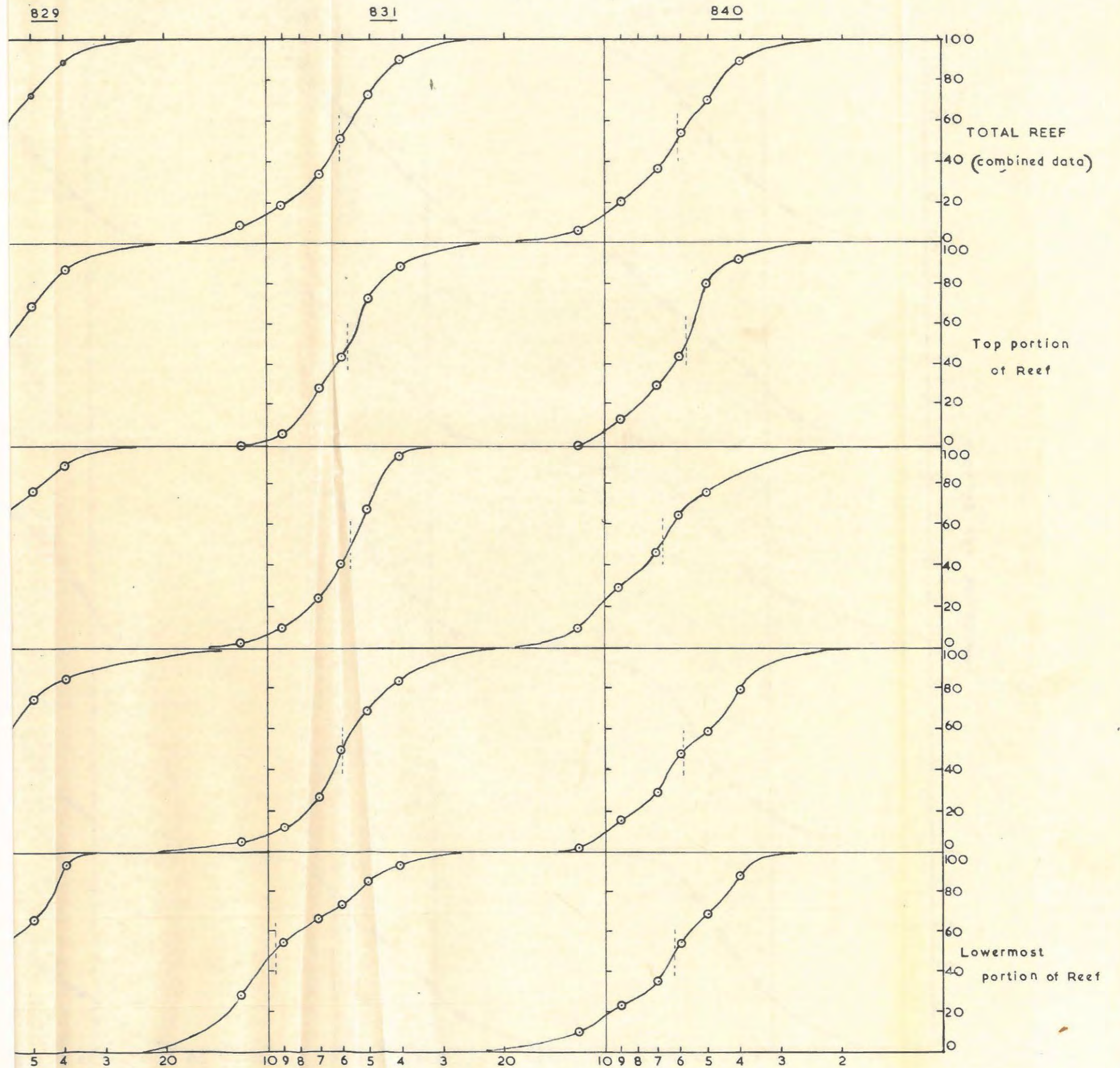
not:

of Rect



GRAIN SIZE 11

FOR PEBBLES IN THE VAAL REEF.



N.M.M. logarithmic scale.

(dashed lines show median pebble sizes)

FIG. 10

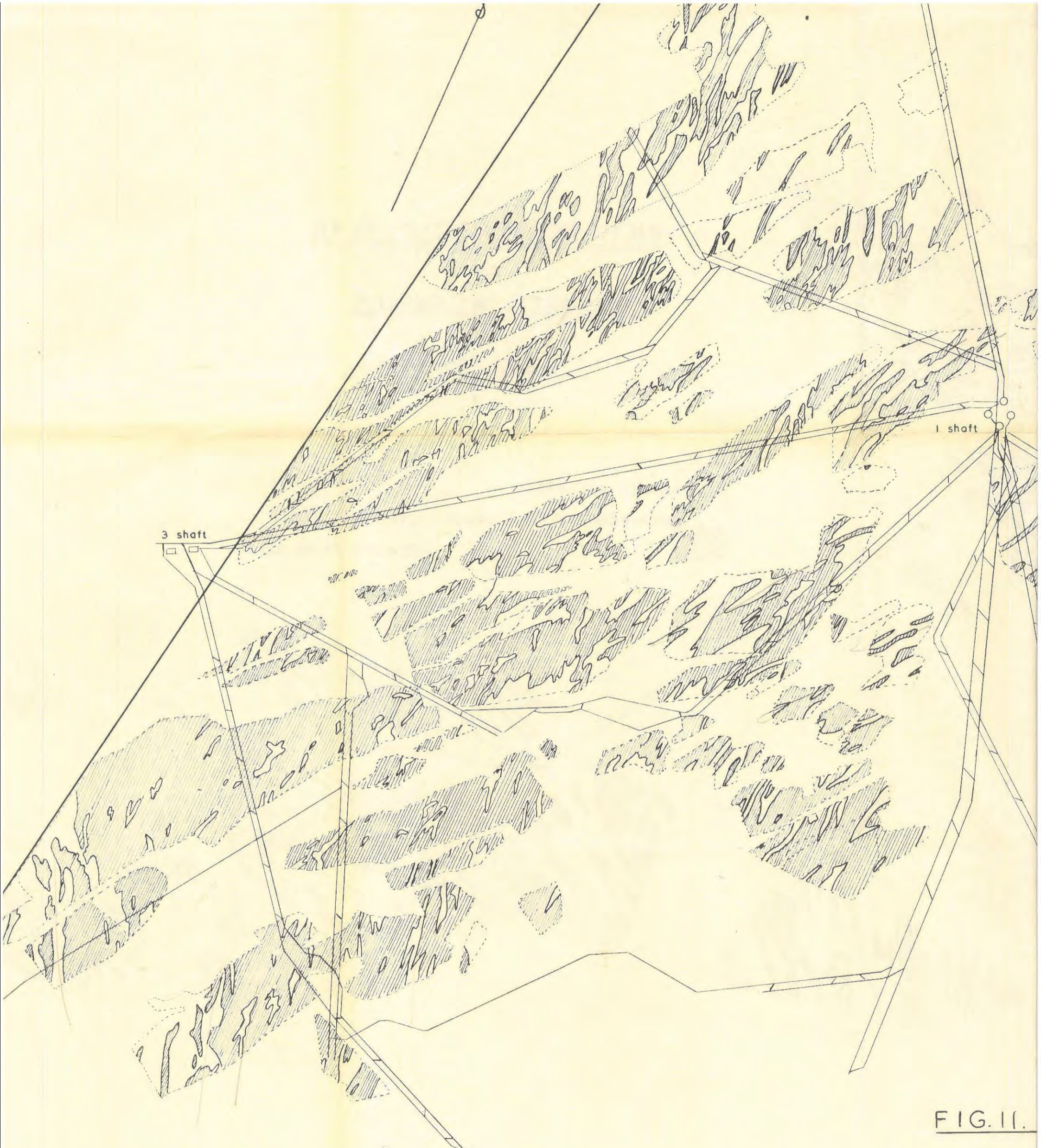


FIG. II.

V A A L R

INCH-PENNYWEIGHT PLAN

OF

VAAL REEF WORKINGS

SCALE- 1:10,000.

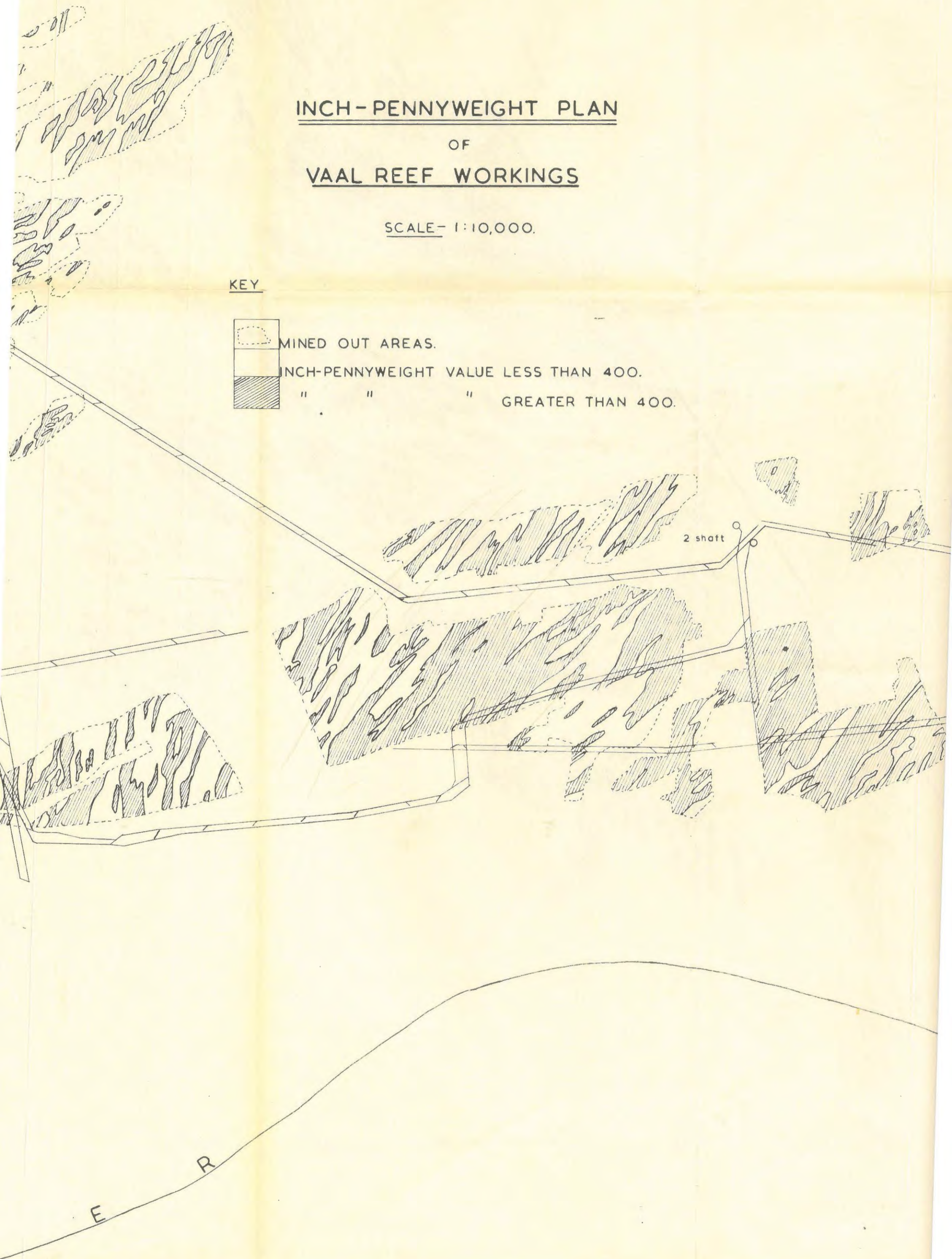
KEY



MINED OUT AREAS.

INCH-PENNYWEIGHT VALUE LESS THAN 400.

" " " GREATER THAN 400.



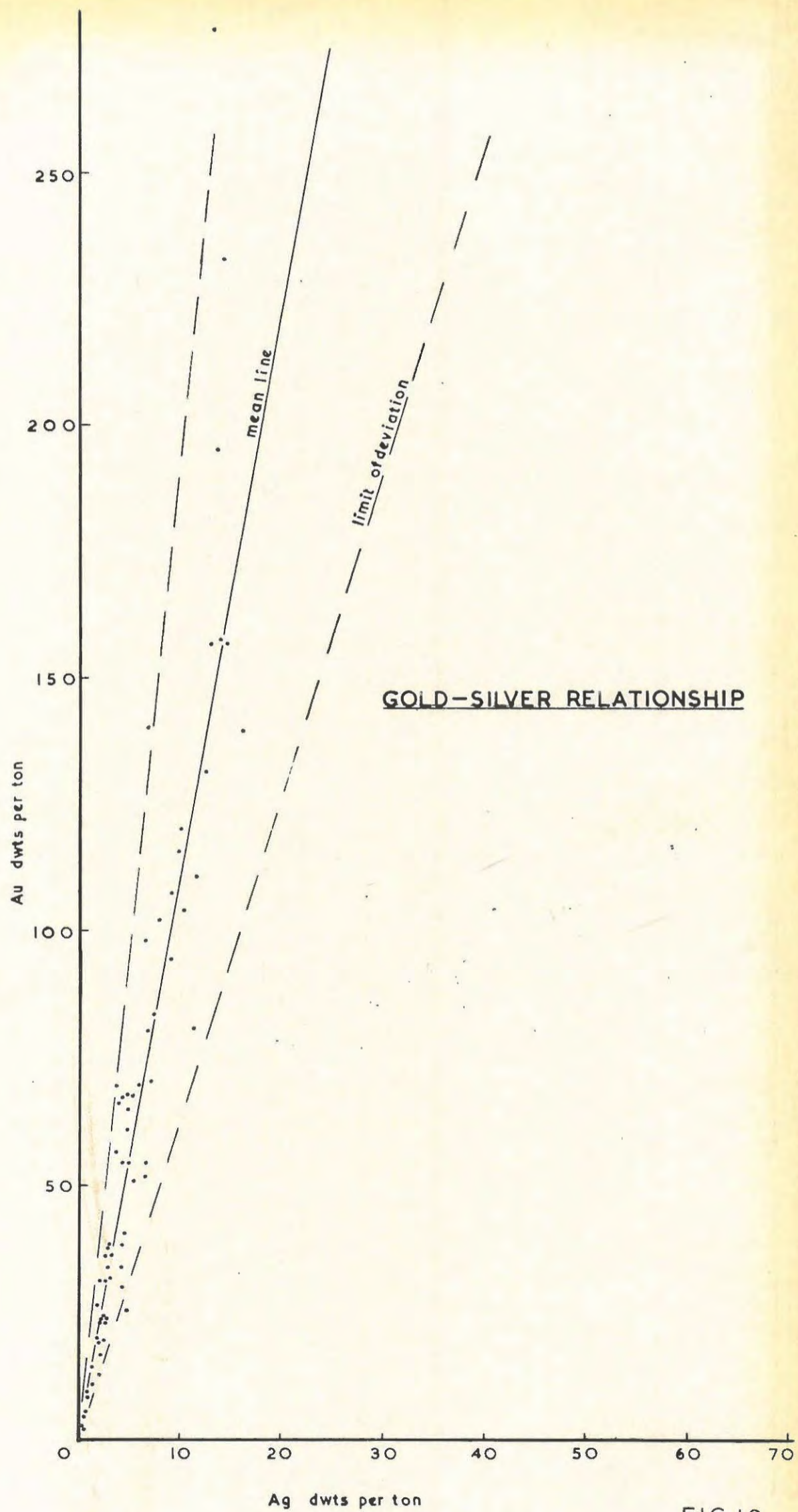


FIG. 12.

14, 12

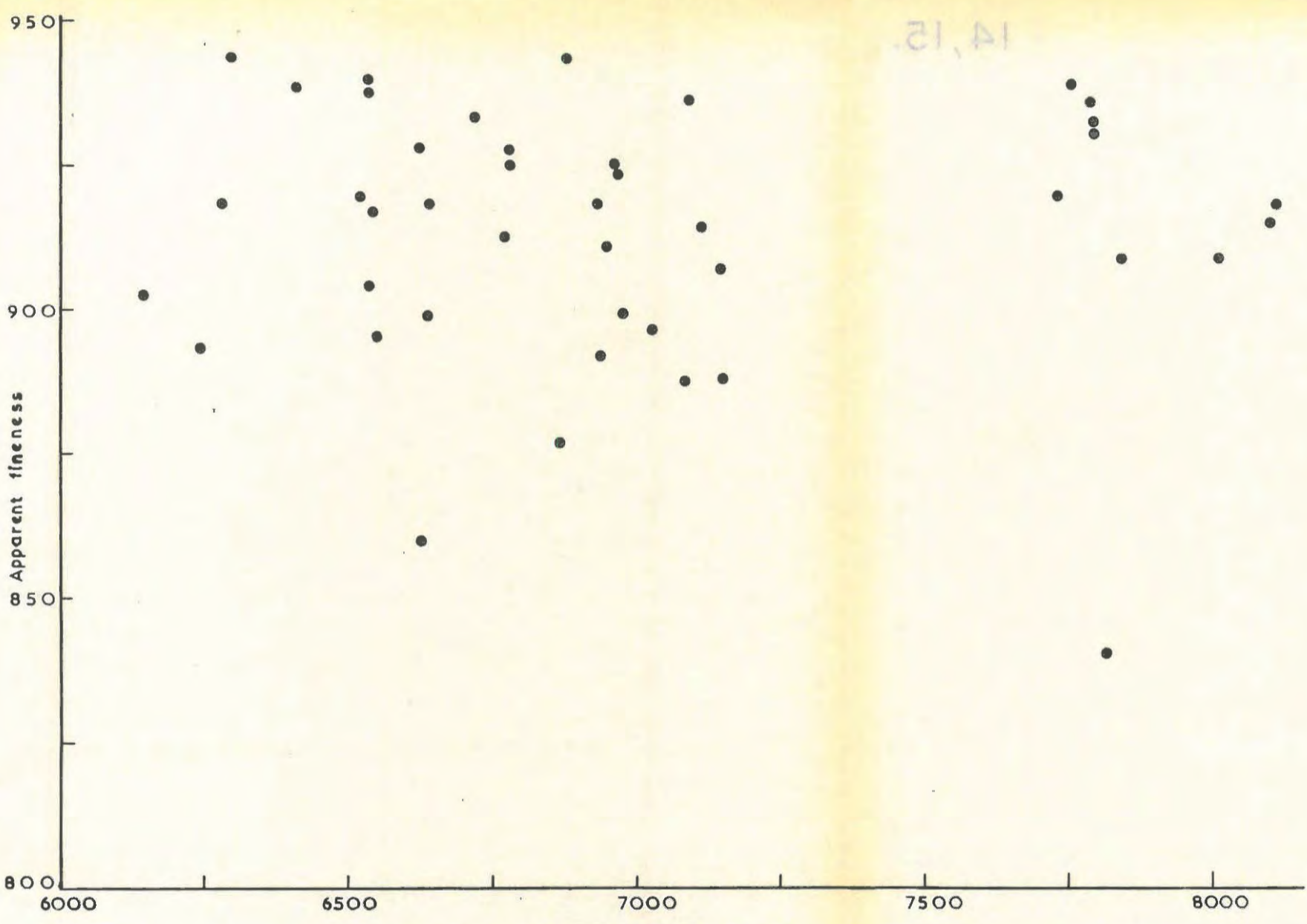


FIG. 14.

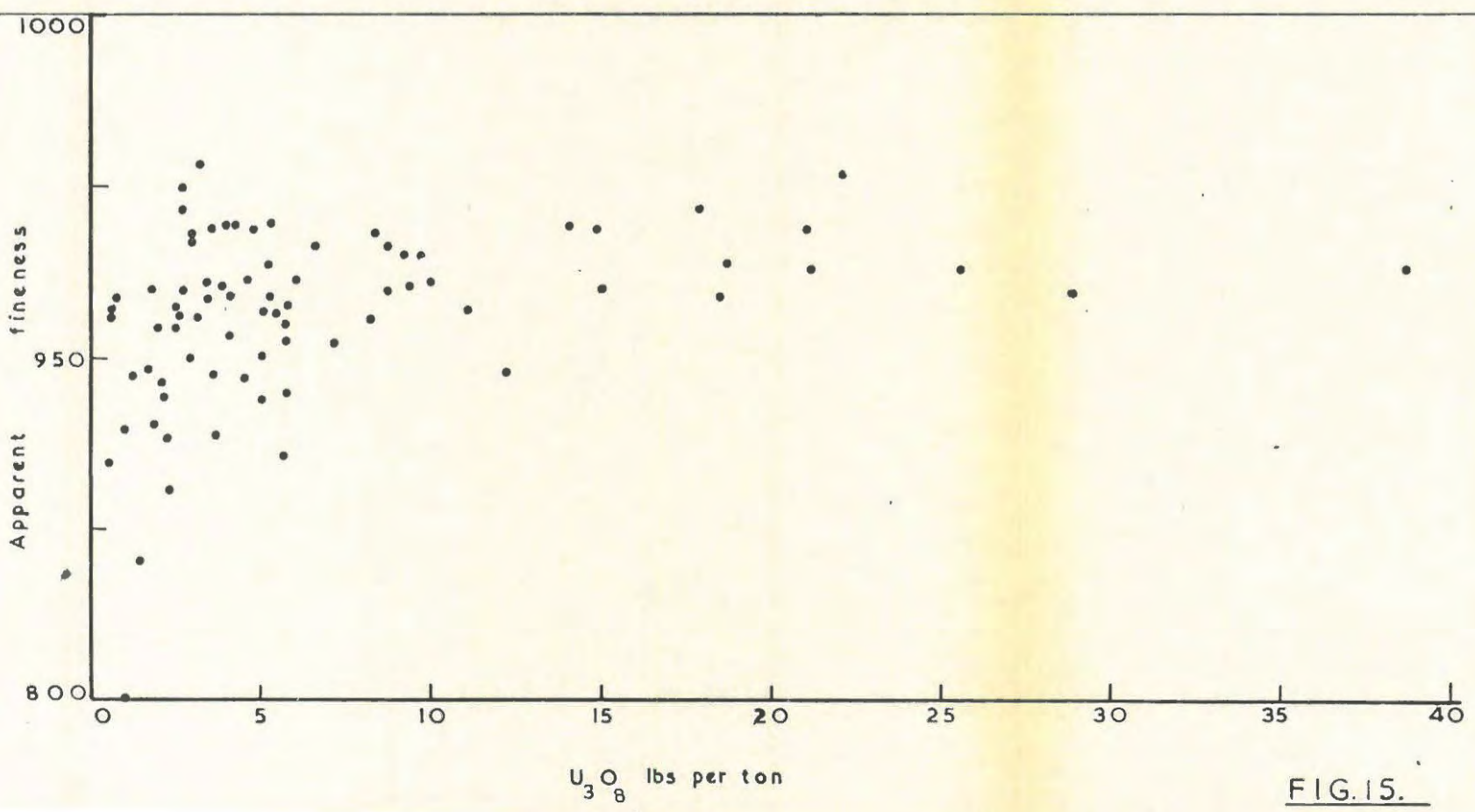


FIG. 15.

GOLD-URANIUM RELATIONSHIP

HIGH GRADE ORE



FIG. 16.

GOLD - URANIUM RELATIONSHIP

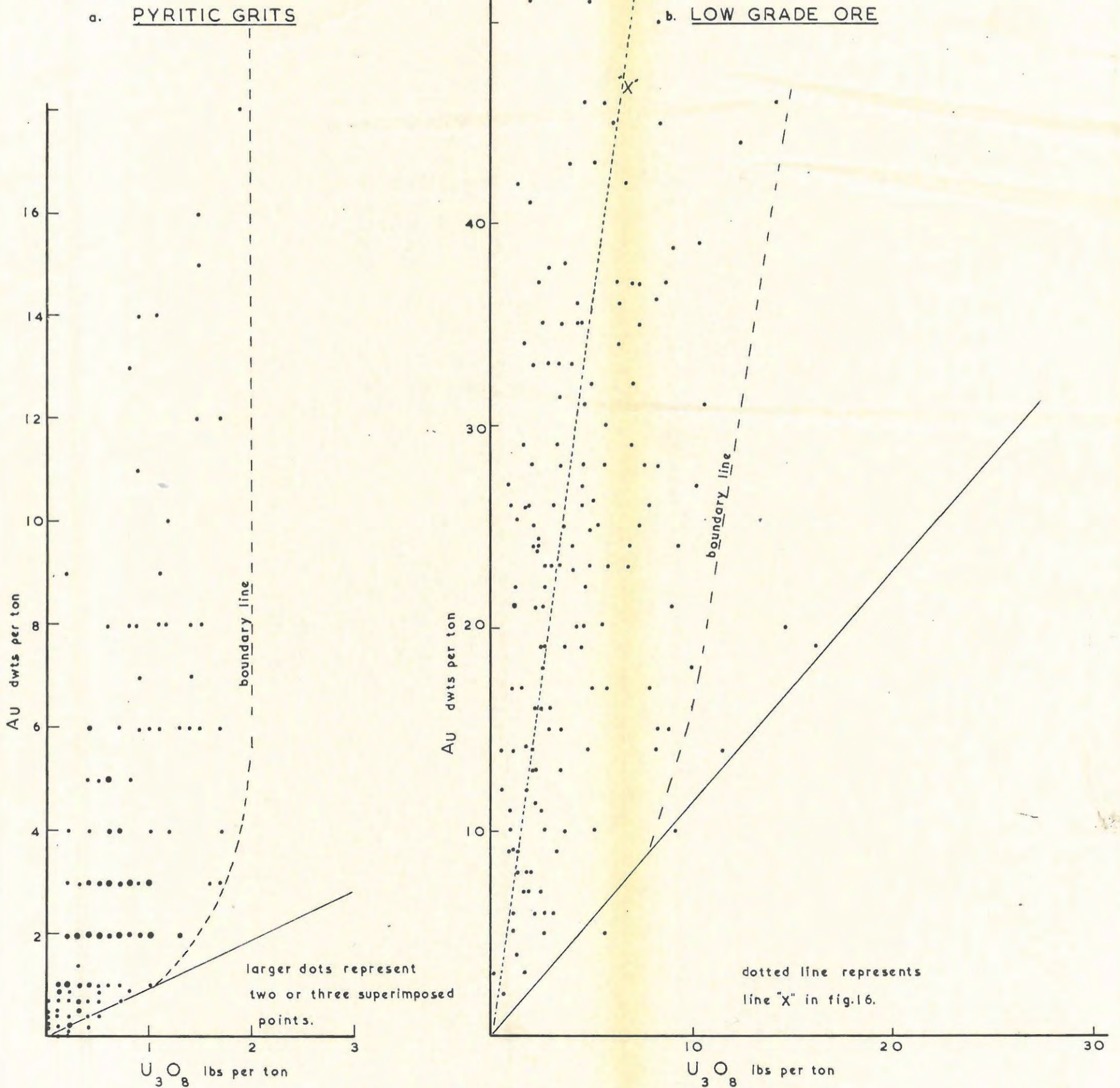
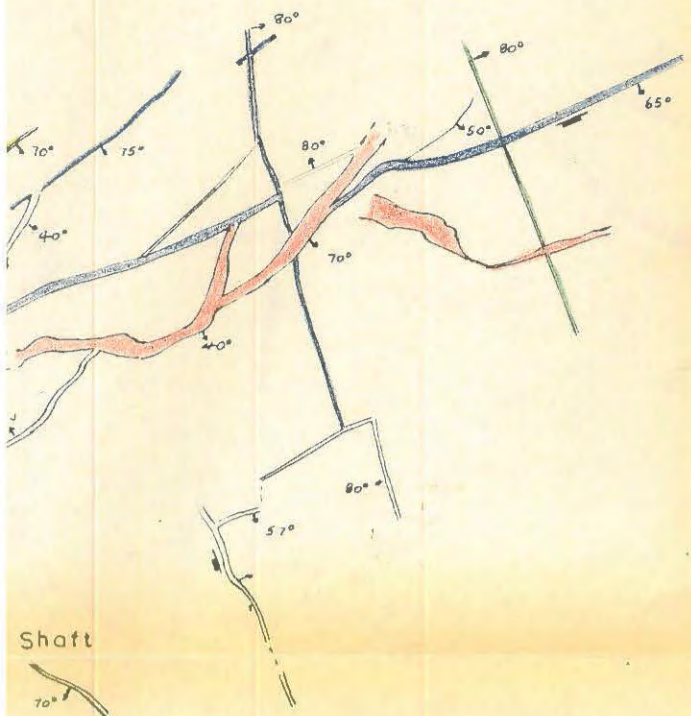


FIG.17.



SCALE - 1:10,000



KEY

[Yellow box]	LAMPROPHYRE
[Pink box]	CARBONATITE
[Orange box]	MOTTLED MICRODIORITE
[Red box]	ILMENITE MELA-MICRODIORITE
[Blue box]	AMYGDALOIDAL DIABASE
[Teal box]	PORPHYRITIC FEATHERY DIABASE
[Light green box]	PORPHYRITIC QUARTZ DIABASE
[Dark green box]	NON-PORPHYRITIC QUARTZ DIABASE
[White box]	unknown - not observed

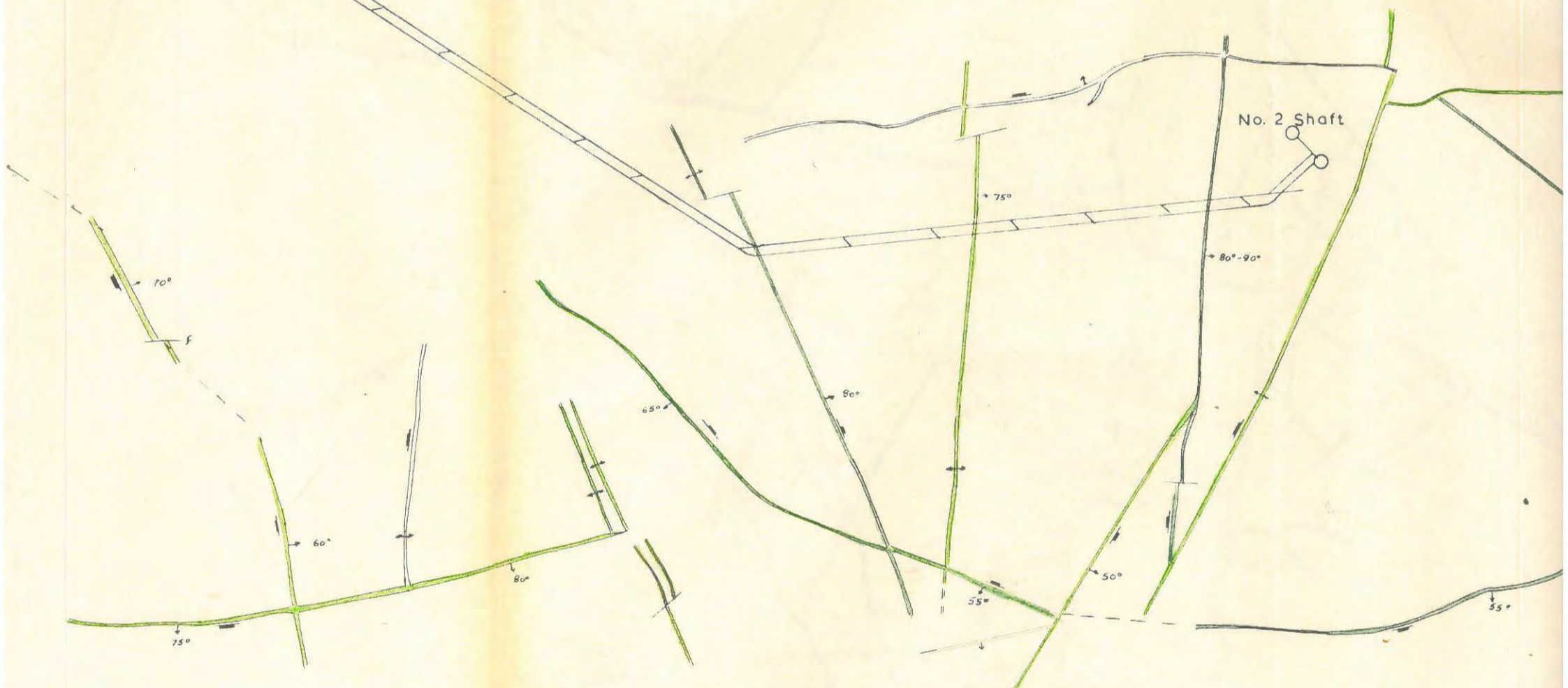
- - - - - dyke projected through fault loss

↙ 70° direction and amount of dip

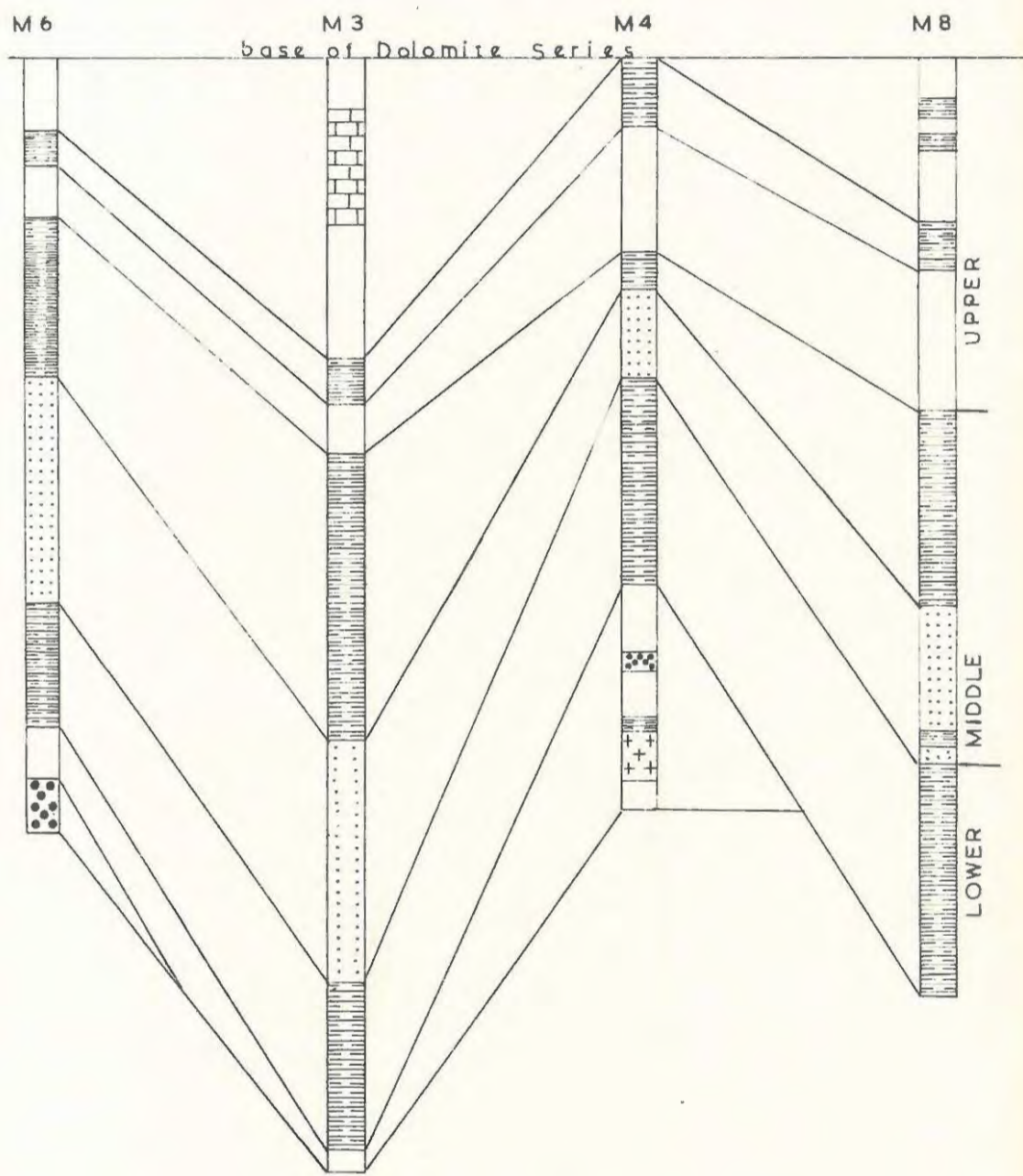
— direction of downthrow

Shaft

No. 2 Shaft



B  
V  
E  
R



TRANSVAAL SYSTEM

BLACK REEF SERIES

SCALE - 1 inch = 10 ft

KEY





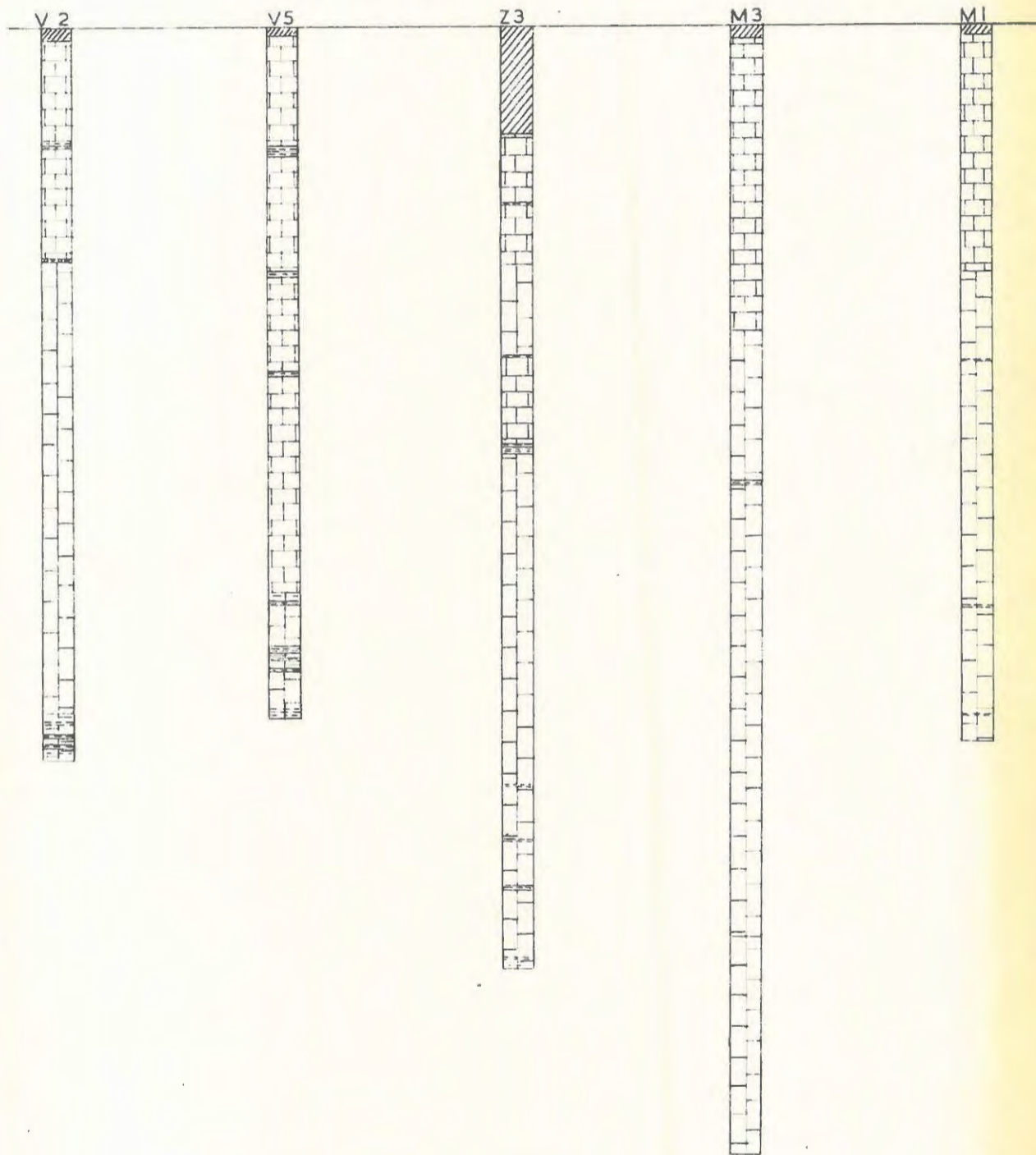
-  shale
-  Middle quartzite
-  Lower and Upper quartzite
-  conglomerate

FIG. 20.



TRANSVAAL SYSTEM

DOLOMITE SERIES

Scale - 1 inch = 200 ft.

KEY





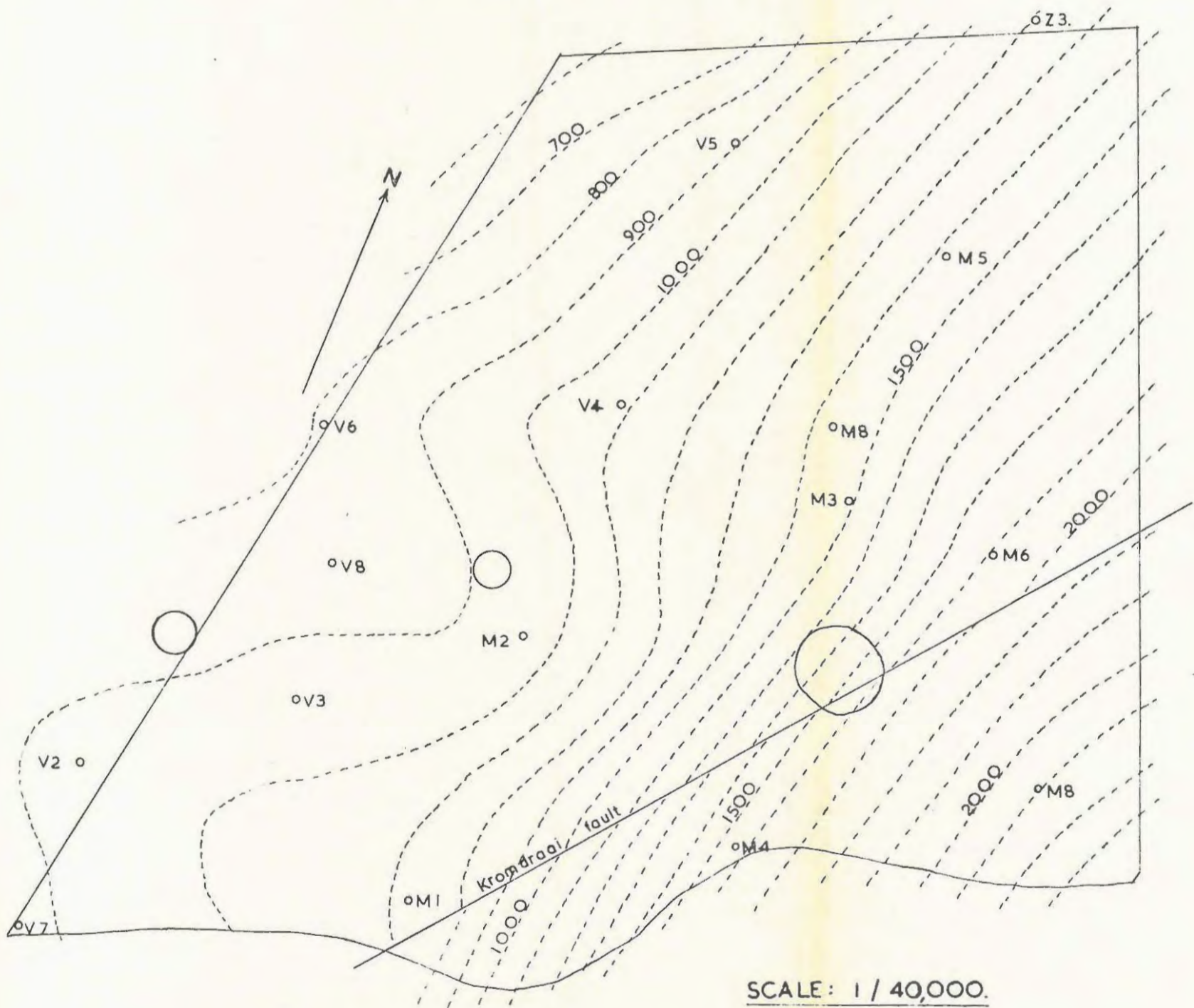
-  soil and weathered dolomite
-  black shale
-  light grey dolomite
-  darker grey dolomite

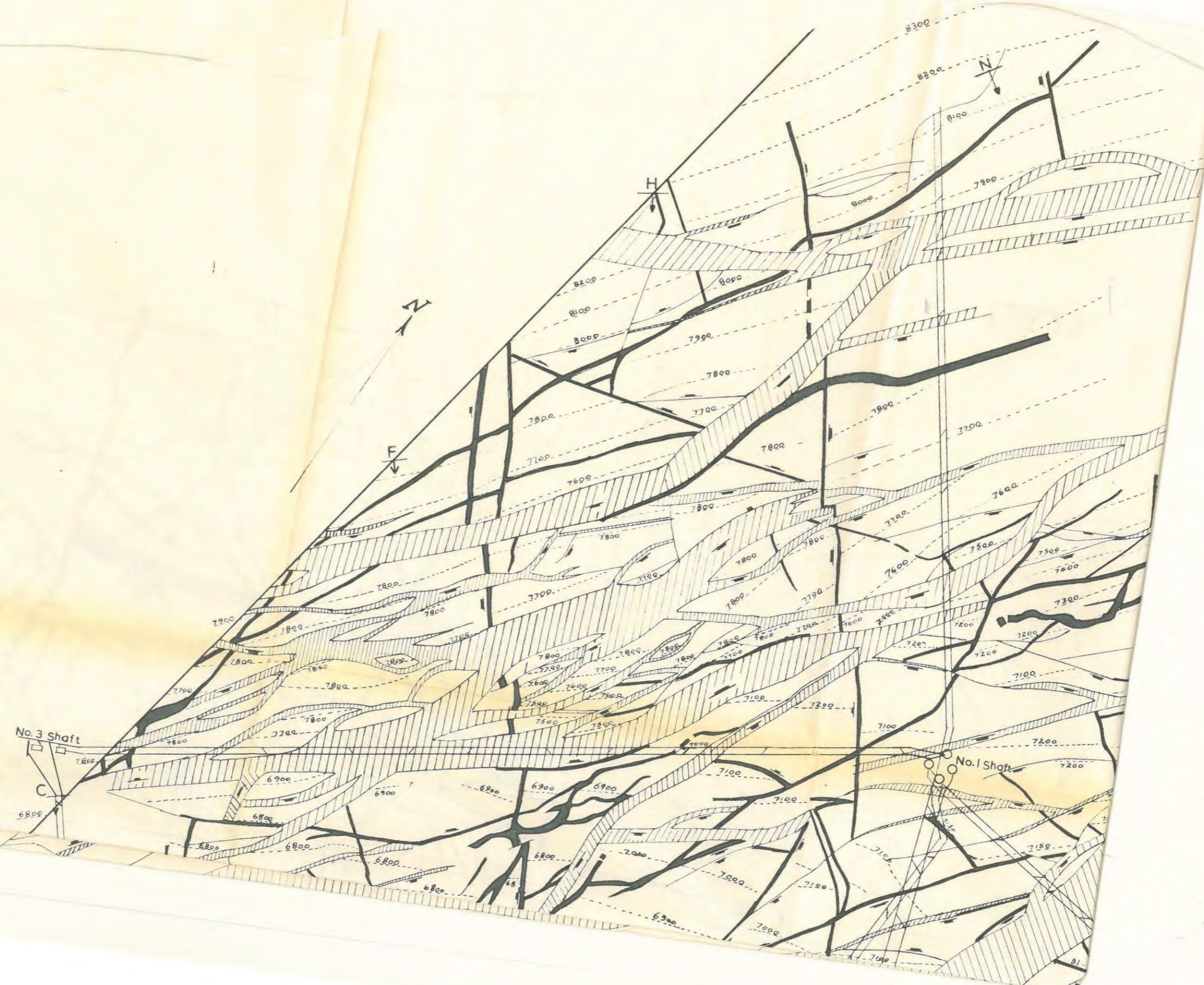
FIG. 21.

ISOPACH MAP  
OF  
TRANSVAAL SYSTEM



- OV 7 boreholes
- shaft pillars
- - - contours at 100ft. intervals.

FIG. 22.



No. 3 Shaft

No. 1 Shaft

N

N

F

H

C

6800

7800

7700

7900

7800

7800

7800

7700

7600

7800

7900

8100

8200

8000

8300

8100

8000

7900

7800

7700

7600

7500

7400

7300

7200

7100

7000

6900

6800

6700

6600

6500

6400

6300

6200

6100

6000

5900

5800

5700

5600

5500

5400

5300

5200

5100

5000

4900

4800

4700

4600

4500

4400

4300

4200

4100

4000

3900

3800

3700

3600

3500

3400

3300

3200

3100

3000

2900

2800

2700

2600

2500

2400

2300

2200

2100

2000

1900

1800

1700

1600

1500

1400

1300

1200

1100

1000

900

800

700

600

500

400

300

200

100

0

-100

-200

-300

-400

-500

-600

-700

-800

-900

-1000

-1100

-1200

-1300

-1400

-1500

-1600

-1700

-1800

-1900

-2000

-2100

-2200

-2300

-2400

-2500

-2600

-2700

-2800

-2900

-3000

-3100

-3200

-3300

-3400

-3500

-3600

-3700

-3800

-3900

-4000

-4100

-4200

-4300

-4400

-4500

-4600

-4700

-4800

-4900

-5000

-5100

-5200

-5300

-5400

-5500

-5600

-5700

-5800

-5900

-6000

-6100

-6200

-6300

-6400

-6500

-6600

-6700

-6800

-6900

-7000

-7100

-7200

-7300

-7400

-7500

-7600

-7700

-7800

-7900

-8000

-8100

-8200

-8300

-8400

-8500

-8600

-8700

-8800

-8900

-9000

-9100

-9200

-9300

-9400

-9500

-9600

-9700

-9800

-9900

-10000

STRUCTURAL PLAN  
SHOWING FAULTS, INTRUSIVES  
AND VAAL REEF CONTOURS.

SCALE - 1:10,000

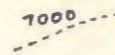
KEY



FAULT LOSSES



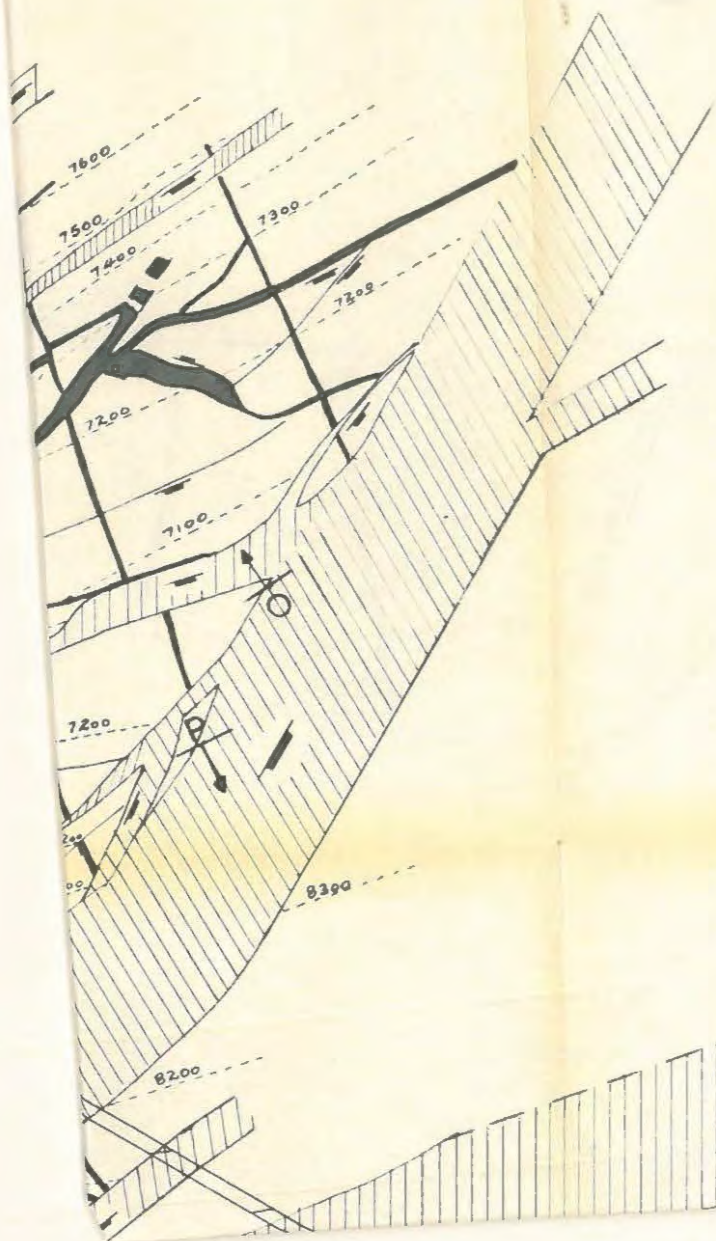
INTRUSIVES

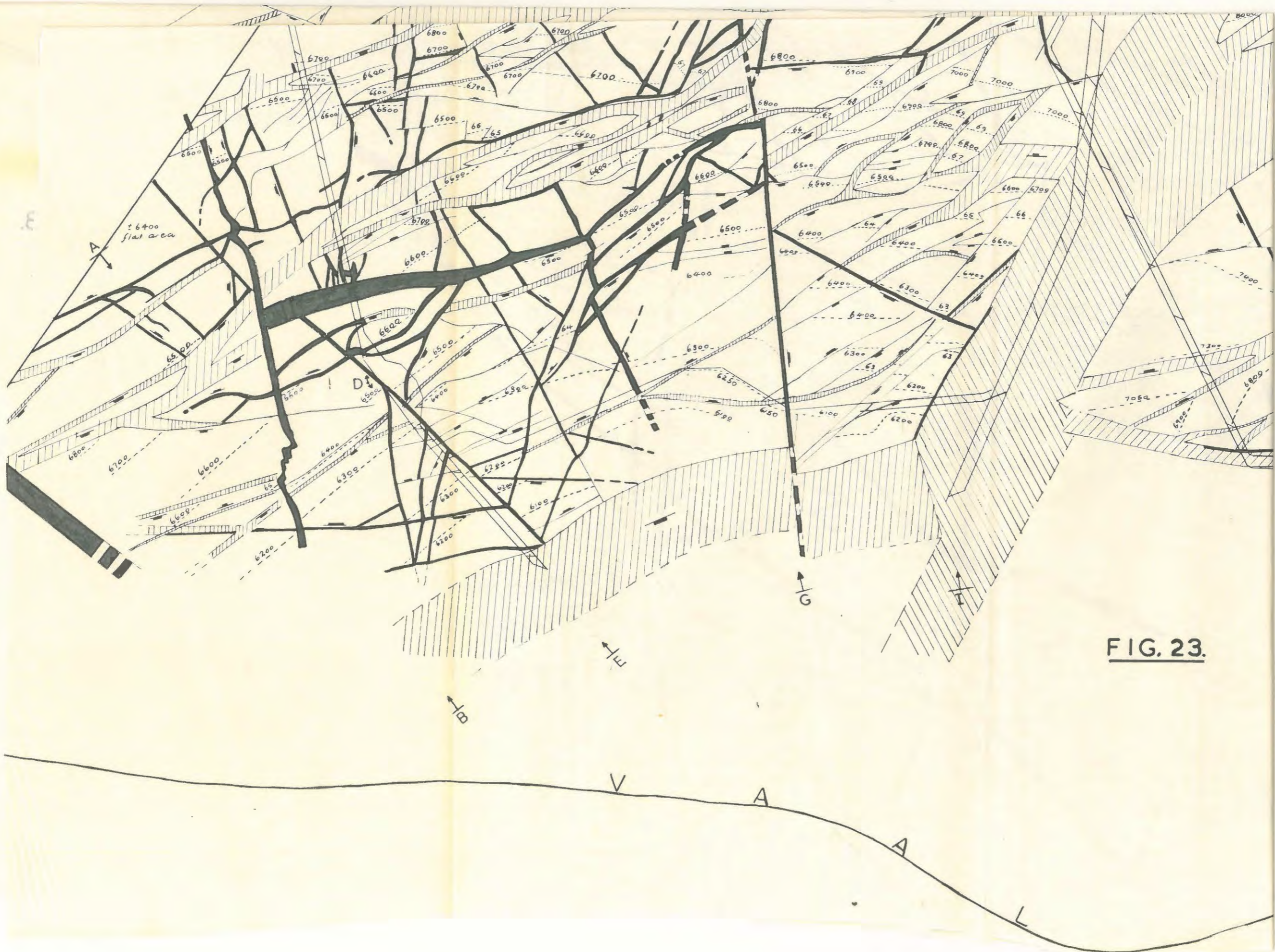


VAAL REEF CONTOURS BELOW 6,000 FT. DATUM.

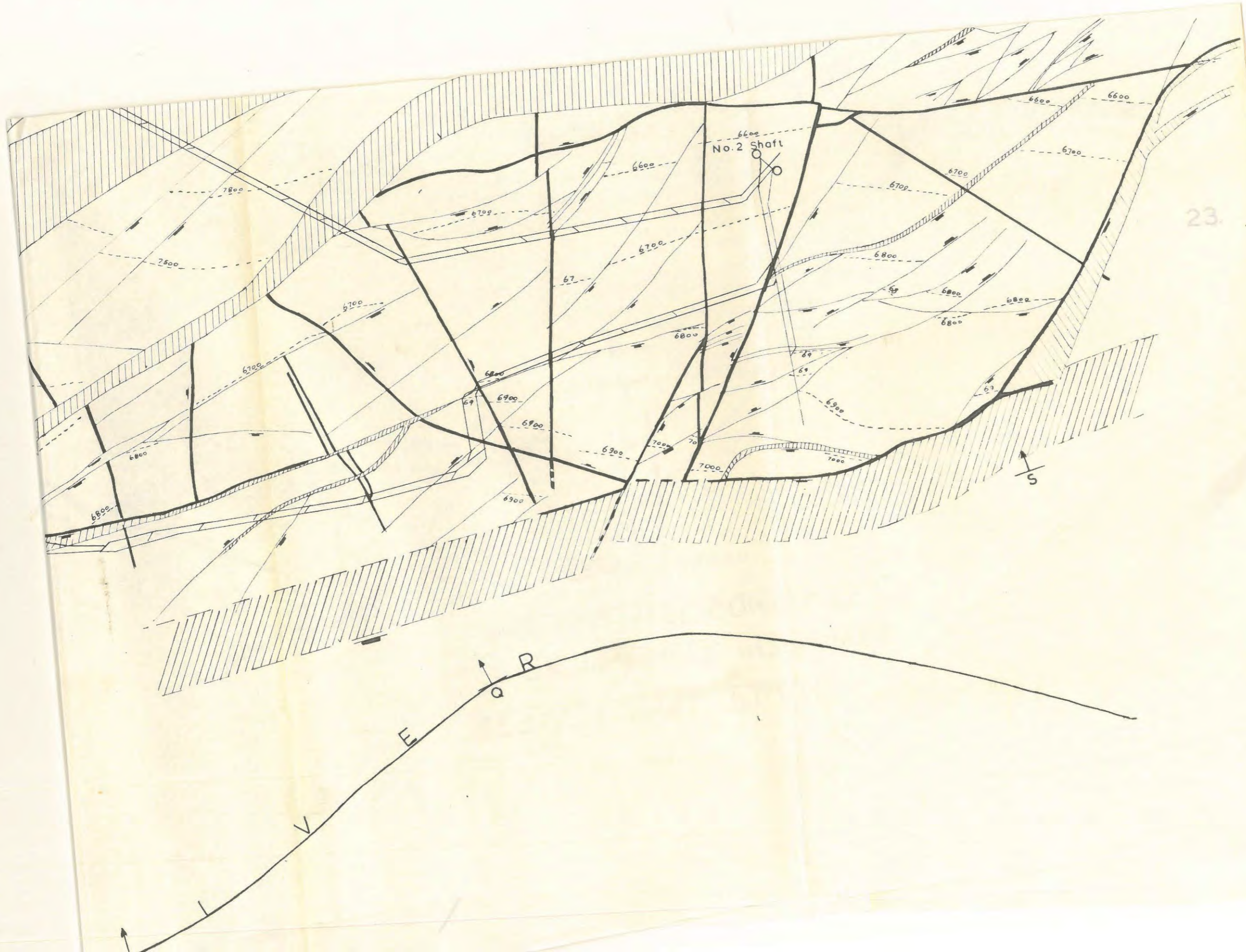


SECTION LINES (see Figs. 24, 25).

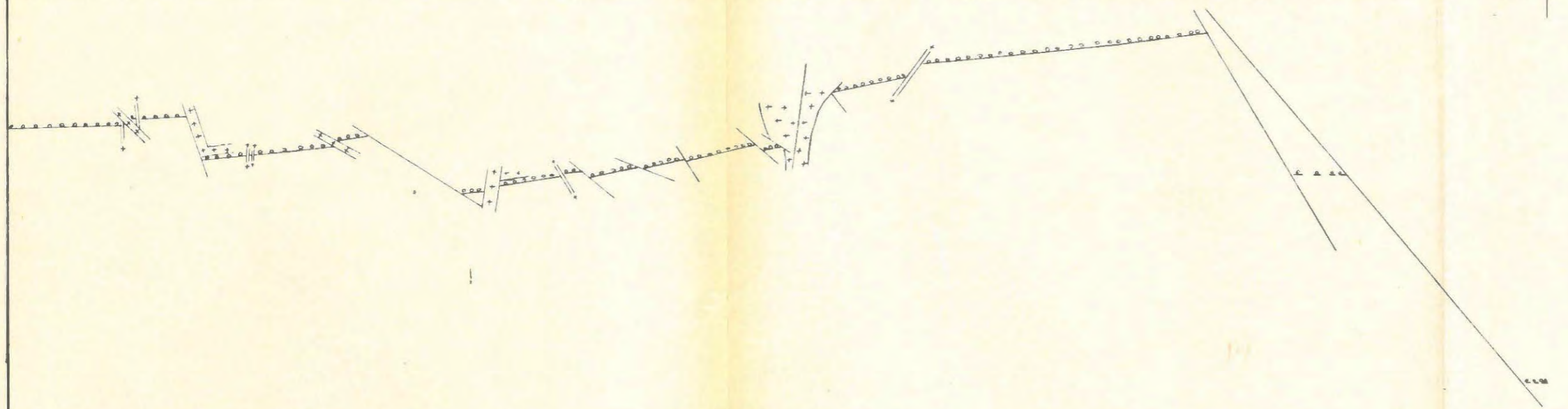




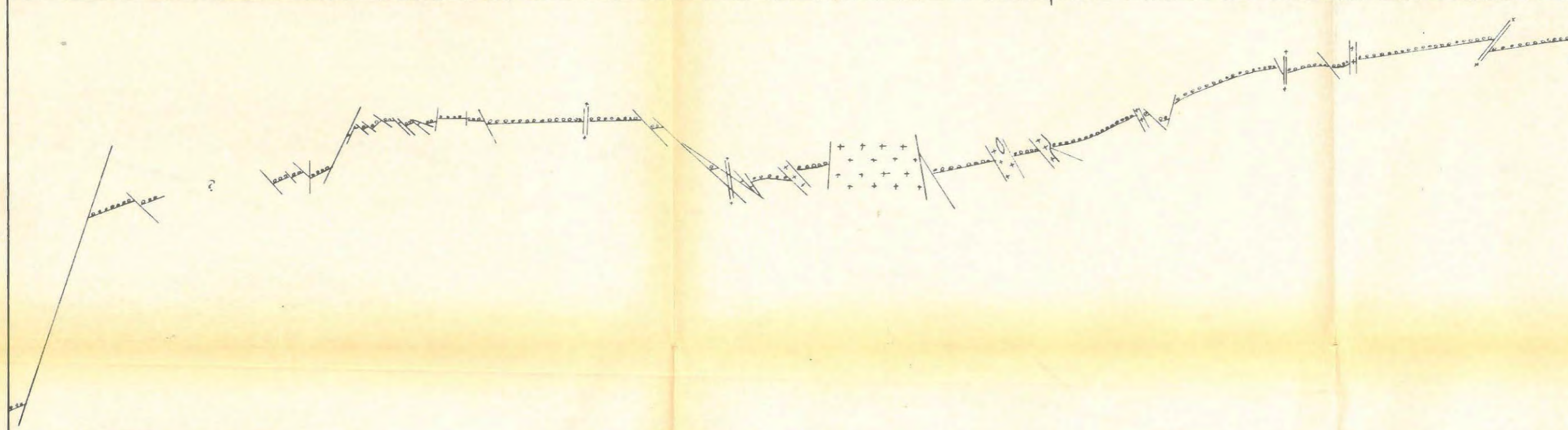
**FIG. 23.**



A DATUM: 6000' BELOW 6000' DATUM i.e. DATUM AT SEA LEVEL B



C DATUM- SEA LEVEL D



F DATUM- SEA LEVEL



GEOLOGICAL SECTIONS ACROSS VAAL REEFS

ILLUSTRATING THE STRUCTURE

AT VAAL REEF ELEVATION

SCALE - 1 : 5,000

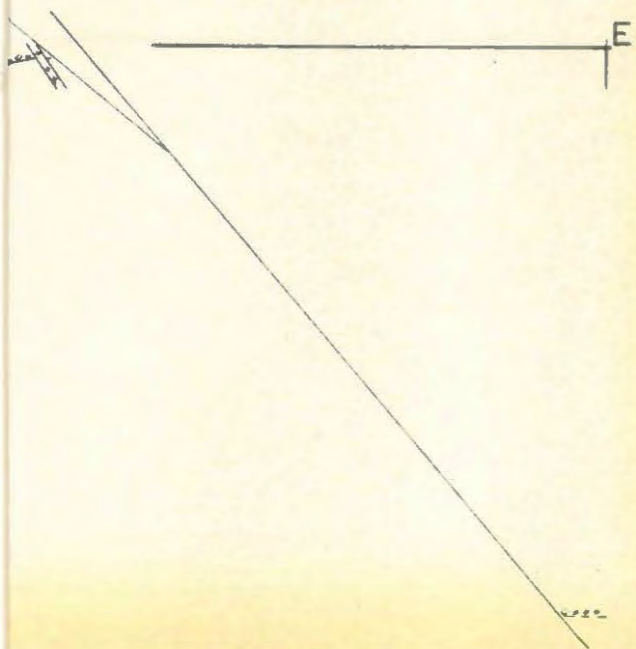
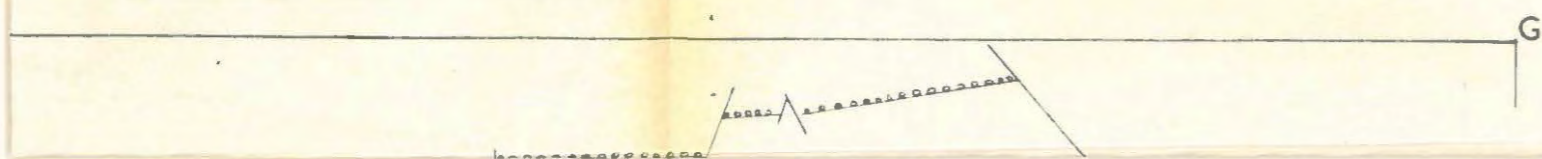
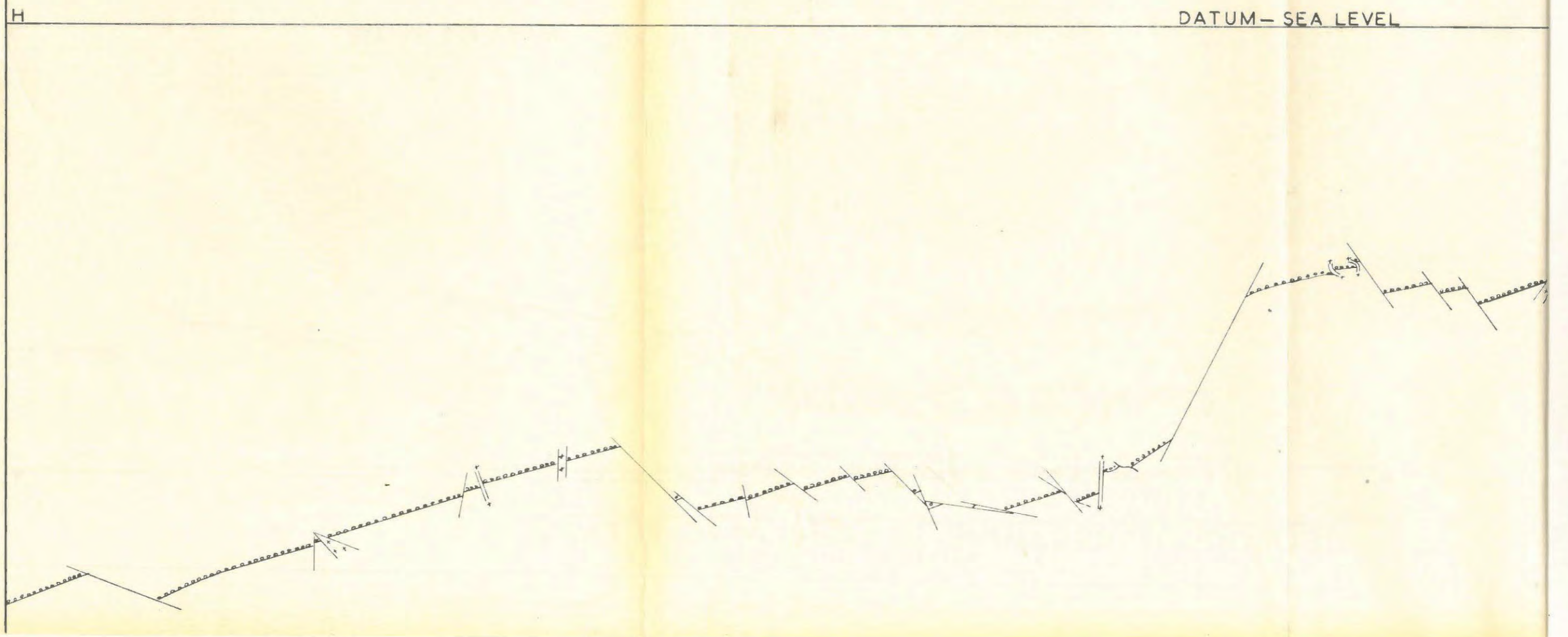
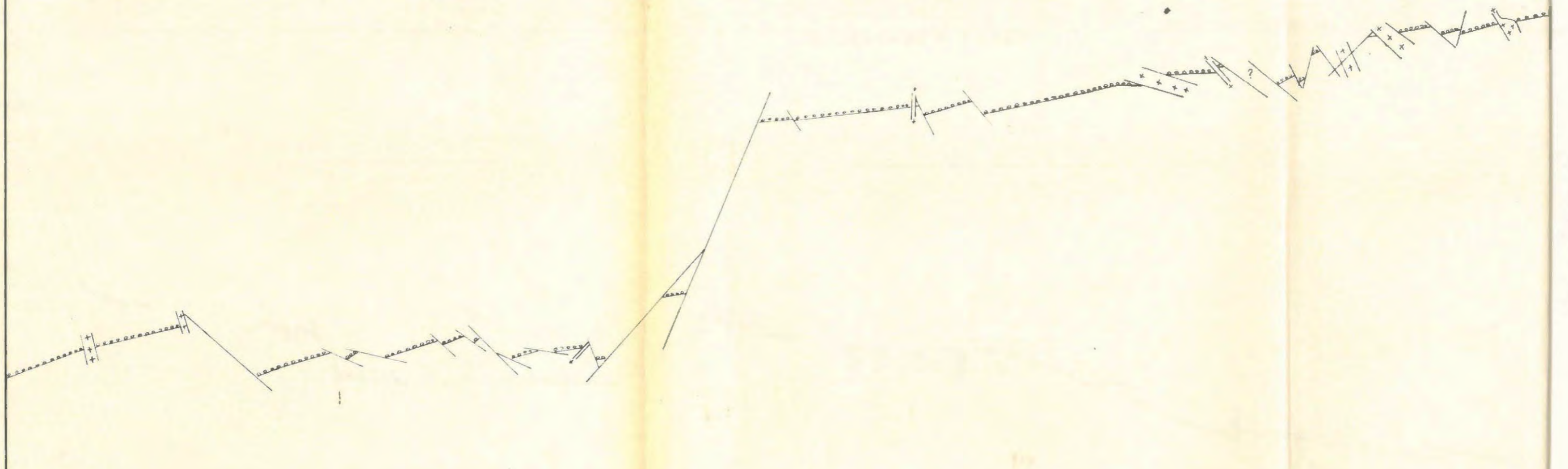


FIG. 24.

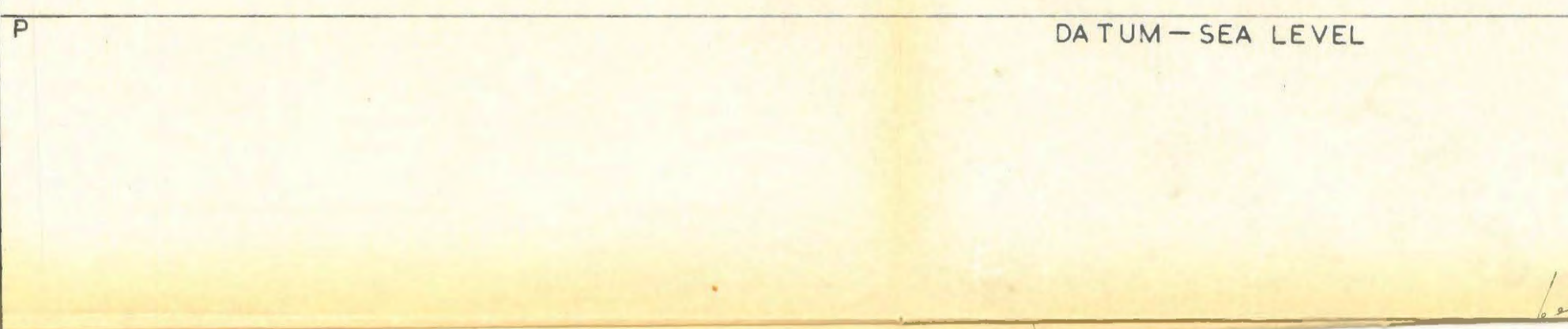
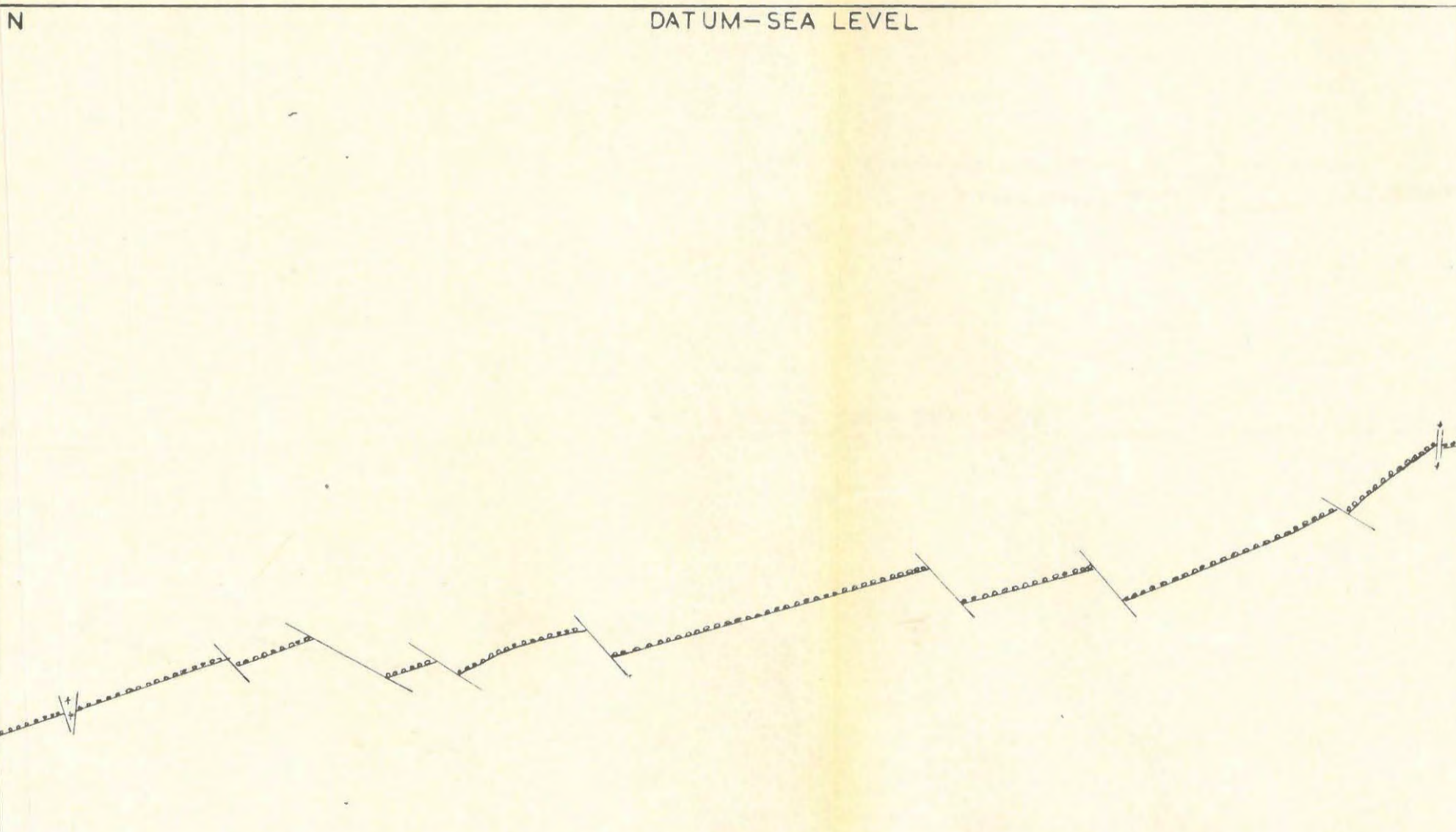
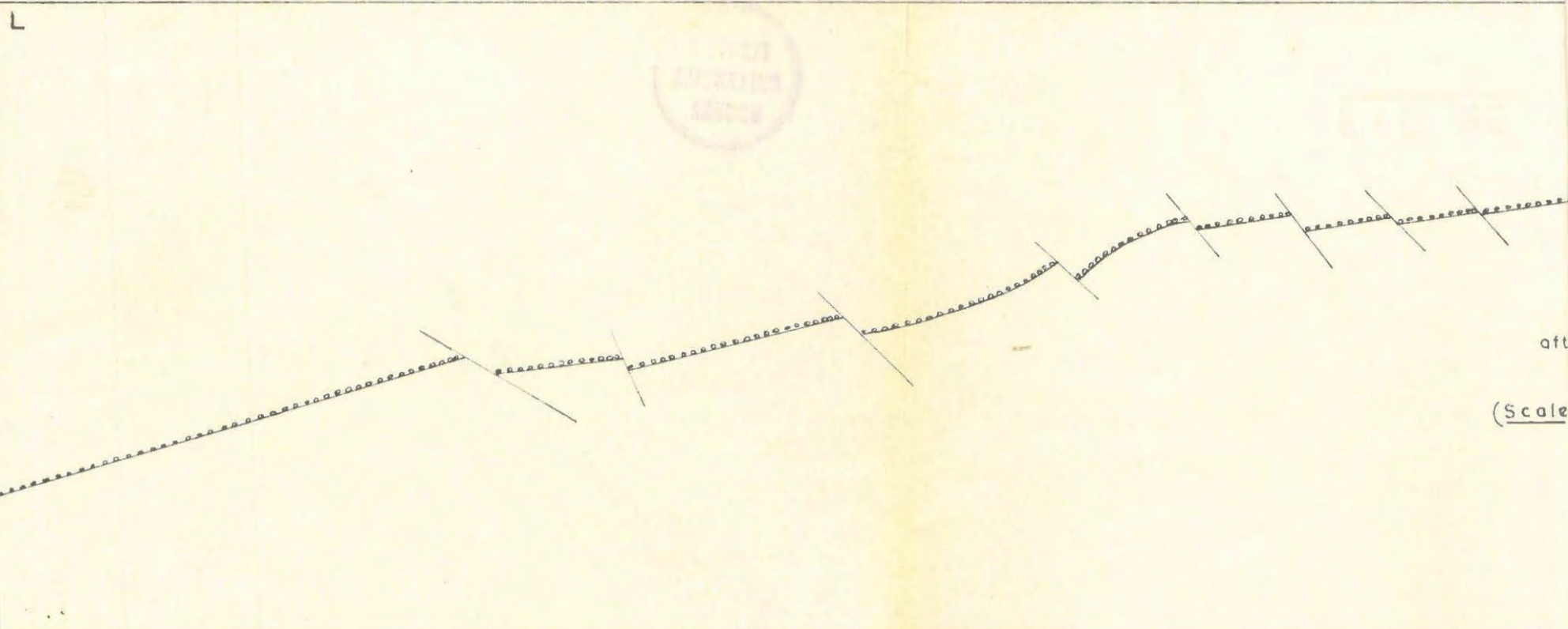


54





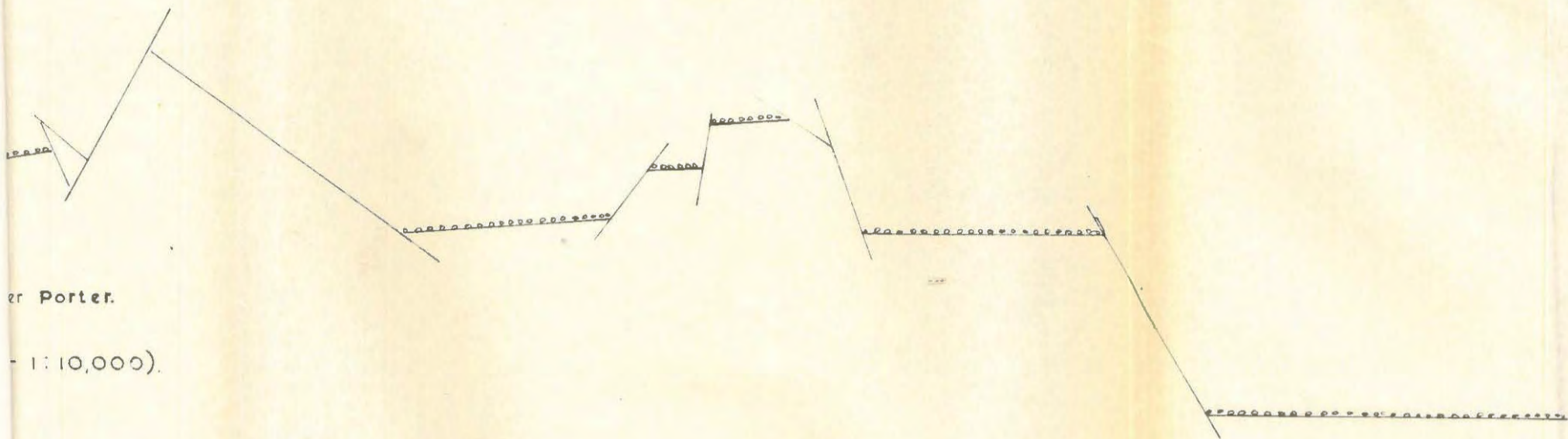
GEOLOGICAL SECTION



102

ONS - CONTINUED.

DATUM - SEA LEVEL

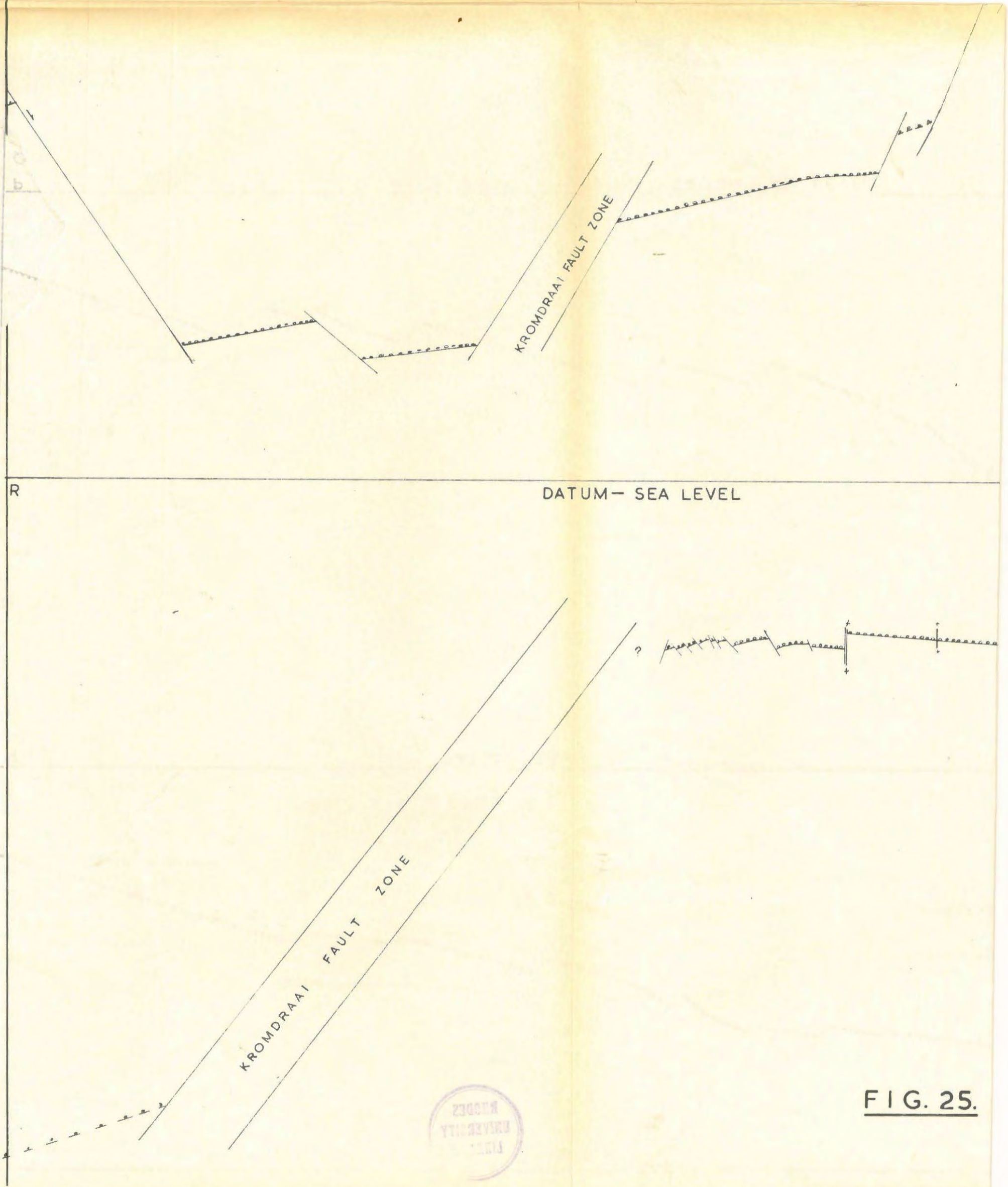


er Porter.

- 1:10,000).

0

0



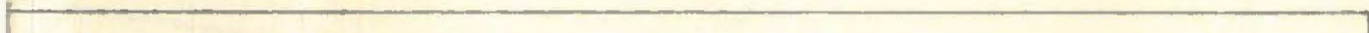
RHODES  
UNIVERSITY  
LIBRARY

FIG. 25.

22



S



S

W