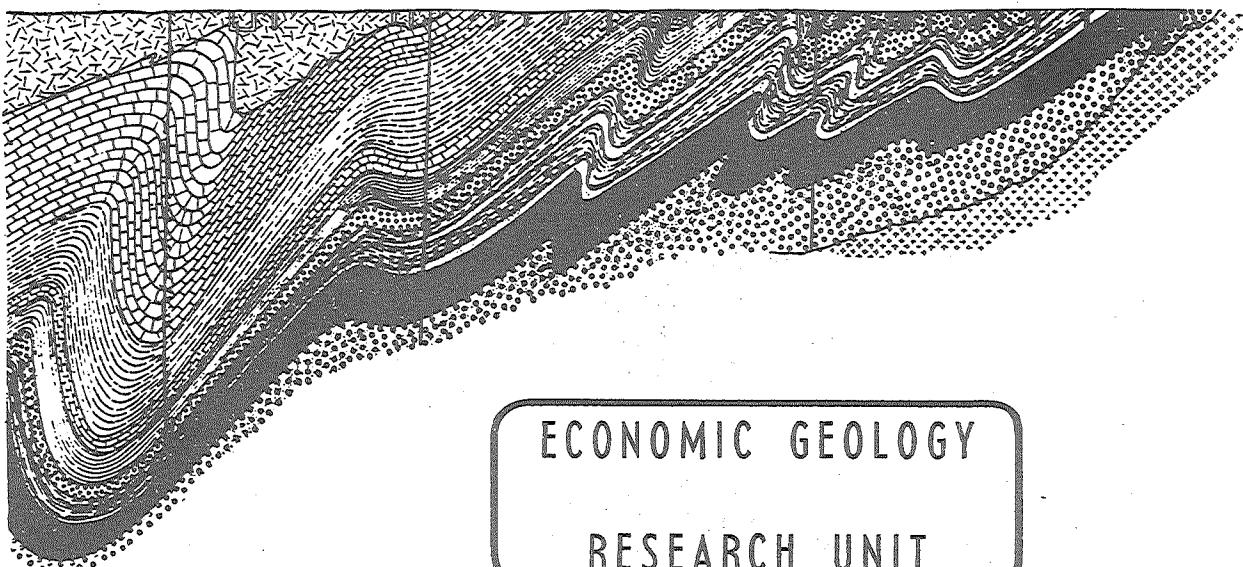




UNIVERSITY OF THE WITWATERSRAND
JOHANNESBURG



INFORMATION CIRCULAR No. 40

THE COMPOSITION OF THE MAIN REEF
AND MAIN REEF LEADER CONGLOMERATE
HORIZONS IN THE NORTHEASTERN PART OF
THE WITWATERSRAND BASIN

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by

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ECONOMIC GEOLOGY RESEARCH UNIT

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ABSTRACT

This investigation deals with the mineralogy and petrology of the Main Reef and Main Reef Leader from a qualitative point of view. The reefs studied have been, and still are, important gold carriers, although uranium is of minor importance, from an economic point of view. The mineralogy has been studied with the aid of thin-sections, polished-sections and polished slabs. A full description and a discussion of origin of all the mineral species observed are given. Classification of the mineral components followed the conventional groupings of alloigenic constituents of the matrix, pebbles, authigenic constituents of the matrix, and ore minerals.

Most of the pebbles consist of vein quartz, although chert, quartz porphyry, quartzite, and schist pebbles were also observed. The chloritoid schist pebbles of the Main Reef Leader of the Central Rand are believed to have been derived mainly from the chloritoid-bearing Black Bar footwall horizon. Of interest is the occurrence of relatively large amounts of columnar quartz which is thought to have resulted from growth in some type of stress field. Chloritoid was found to be a useful mineral as an aid in correlation, and also as an indicator of the original composition of the matrix material. Whereas the mineral is completely lacking in the Main Reef Leader of the East Rand, it is almost invariably present, in varying amounts, in the matrix of the Main Reef Leader of the Central Rand and in the Main Reef. Pyrite, in a number of varieties, was found to be the most abundant ore mineral in all the reefs studied, and three stages of pyrite mineralization have been recognized. Pyrrhotite is generally abundant in the Main Reef Leader of the East Rand and in the Main Reef Leader of the Central Rand, but is usually lacking in the Main Reef. Small flakes of pyrrhotite are commonly associated with uraninite grains. The formation of most of the pyrrhotite in the Main Reef Leader and Main Reef Leader (East Rand) is thought to be due to the dissociation of suitable open-textured pyrite which attained this form due to tectonic fracturing. The formation of pyrrhotite flakes in close association with uraninite grains is believed to be due to a process such as radioactive heating. Thucholite was possibly derived from hydrocarbons produced by primitive organic life-forms which grew in depositional depressions under favourable conditions. Rounded grains of arsenopyrite (plus cobaltite and glaucodot) were found to be wide-spread constituents of the reefs studied. The close association of skutterudite and linnaeite with gold is distinctive in samples rich in the latter mineral. This association is thought to be due to the reconstitution of original detrital material which was in close proximity to the gold. Most of the pyrite, arsenopyrite, gold and uraninite are believed to be of detrital origin. A tentative paragenetic chart, depicting the main phases of mineralization of ore minerals within the reefs studied, has been compiled.

The possibility of correlating reef horizons through their mineralogical characteristics is discussed.

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THE COMPOSITION OF THE MAIN REEF AND
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THE NORTHEASTERN PART OF THE WITWATERSRAND BASIN

INTRODUCTION

A. SOURCE OF MATERIAL INVESTIGATED

In this investigation, the qualitative aspects of the petrology and mineralogy of the Main Reef and Main Reef Leader conglomerate horizons of the Central, East, and West Rand areas, as well as of the Main Reef of the West Wits Line, have been studied in detail in the laboratory. The reefs belong to the Main Stage of the Main-Bird Series of the Upper Division of the Witwatersrand System.

The Main Reef horizon usually forms the lowermost of the consistently payable conglomerate bands, and is well-developed in the Central Rand (the type area), the West Rand, and the West Wits Line. It is doubtful whether the reef continues east of the E.R.P.M. Mine.

The Main Reef Leader is, economically speaking, the most important gold-bearing reef on the Central Rand. It is usually thinner than the Main Reef, and is characterized by its considerable areal extent and high, but sometimes erratic, gold values. It usually occurs three feet above the top of the Main Reef, but is frequently in contact with it (Jones, 1936). Over the greater part of the Central Rand, the reef rests on an unstratified chloritoid-bearing mudstone known as the Black Bar. This narrow band of dark shale varies from six inches to one foot in thickness in the mines near Johannesburg. From the Consolidated Main Reef Mine westwards, it dwindles to a few inches, becomes intermittent, and is frequently absent. From the Durban Roodepoort Deep Mine westwards, the Main Reef Leader is, itself, relatively unimportant, and does out in a westerly direction. The Main Reef Leader of the Central Rand has tentatively been correlated with the so-called Main Reef of the East Rand. In order to standardise terminology, this reef will be referred to as the Main Reef Leader (East Rand) throughout this paper. The name varies from mine to mine, and it has also been referred to as the Van Ryn, Nigel, and Main Reef. A number of additional conglomerate bands, with limited areal distributions, occurring within the Main-Bird Series, have been worked along the northwestern rim of the East Rand Basin, in the New Kleinfontein, Van Ryn, and Modder Deep mines. The gold content of the Main Reef Leader (East Rand) and its areal extent and persistence make it one of the most economically important horizons within the Witwatersrand System. The gold is often concentrated in well-defined patches, or payshoots, and the reef itself usually rests on a shale horizon — the Jeppestown shale of the Lower Division of the Witwatersrand System.

The South Reef (not studied in the investigation) occurs about 110 feet above the Main Reef Leader in the type area, and is economically important in the Central Rand and the West Rand. Correlation of this reef with the Main Reef Leader (East Rand) has been suggested.

In the eastern section of the E.R.P.M. Mine, the underlying Main Reef and Main Reef Leader horizons are apparently successively transgressed by the overlying South Reef, which forms what is known as the Composite Reef. In the area to the east of the E.R.P.M. Mine, there occurs a "break" or "gap" in the gold values of the reef, until economic blanket is encountered again in the East Rand. This "break" in gold values is generally referred to as the "Boksburg Gap", and probably resulted from the deposition of poorly developed reef on an area which was elevated, with respect to the rest of the basin, at the time of reef deposition.

The samples studied were collected from reefs along a total strike length of approximately 120 miles from the Doornfontein Mine in the west, to the Witwatersrand Nigel Mine, at the southeastern extremity of the East Rand, in the east (Figure 1). The east-west extent of this area is about 80 miles. The names of the numbered mines on this map are as follows :

<u>Mine</u>	<u>Abbreviation</u>
1. Witwatersrand Nigel Ltd.	Wit. Nigel
2. Spaarwater Gold Mining Co. Ltd.	Spaarwater
3. The Sub-Nigel Ltd.	Sub-Nigel
4. Vlakfontein Gold Mining Co. Ltd.	Vlakfontein
5. Vogelstruisbuilt Gold Mining Areas Ltd.	Vogelstruisbuilt
6. Marievale Consolidated Mines Ltd.	Marievale
7. East Daggafontein Mines Ltd.	East Daggafontein
8. Daggafontein Mines Ltd.	Daggafontein
9. Springs Mines Ltd.	Springs
10. S.A. Land and Exploration Co. Ltd.	S.A. Lands
11. Van Dyk Consolidated Mines Ltd.	Van Dyk
12. Brakpan Mines Ltd.	Brakpan
13. Government Gold Mining Areas (Modderfontein) Consolidated Ltd.	Government Areas
14. Geduld Proprietary Mines Ltd.	Geduld
15. East Geduld Mines Ltd.	East Geduld
16. Grootvlei Proprietary Mines Ltd.	Grootvlei
17. Modderfontein East Ltd.	Modder East
18. New Kleinfontein Co. Ltd.	New Kleinfontein
19. East Rand Proprietary Mines Ltd.	E.R.P.M.
20. Rietfontein Consolidated Mines Ltd.	Rietfontein
21. Rose Deep Ltd.	Rose Deep
22. Simmer and Jack Mines Ltd.	Simmer and Jack
23. City Deep Ltd.	City Deep
24. Robinson Deep Ltd.	Robinson Deep
25. Crown Mines Ltd.	Crown Mines
26. Consolidated Main Reef Mines and Estates Ltd.	C.M.R.
27. Rand Leases (Vogelstruisfontein) Gold Mining Co. Ltd.	Rand Leases
28. Durban Roodepoort Deep Ltd.	Durban Deep
29. South Roodepoort Main Reef Areas Ltd.	South Roodepoort
30. East Champ D'Or Gold Mining Co. Ltd.	East Champ D'Or
31. Luipaards Vlei Estate and Gold Mining Co. Ltd.	Luipaardsvlei
32. West Rand Consolidated Mines Ltd.	West Rand Cons.
33. Randfontein Estates Gold Mining Co. (Witwatersrand) Ltd.	Randfontein Estates
34. Venterspost Gold Mining Co. Ltd.	Venterspost
35. Libanon Gold Mining Co. Ltd.	Libanon
36. Western Areas Gold Mining Co. Ltd.	Western Areas
37. Western Deep Levels Ltd.	Western Deep Levels
38. West Driefontein Gold Mining Co. Ltd.	West Driefontein
39. Blyvooruitzicht Gold Mining Co. Ltd.	Blyvooruitzicht
40. Doornfontein Gold Mining Co. Ltd.	Doornfontein

The following samples were available for study :

Reef	Number of Samples
Main Reef (West Wits Line, West Rand, Central Rand)	38
Main Reef Leader (Central Rand)	19
Main Reef Leader (East Rand)	59
South Reef (Central Rand)	5
Total	121

B. REASONS FOR THE INVESTIGATION

The study of the mineralogy of the Main Reef and Main Reef Leader was aimed at determining :

- (i) whether variations in the mineralogy of a particular reef horizon are useful as indicators of the mode of deposition of individual conglomerates, and whether these variations are of significance;
- (ii) the possible conditions and environment under which the conglomerate horizons were deposited, and the method of concentration of gold and radioactive minerals within a particular reef;
- (iii) the variation in the nature of the conglomerates and their gold contents progressively away from an assumed point of entry of material into the depositional basin;
- (iv) whether the Main Reef Leader (East Rand) was derived from a source different to that of the Main Reef Leader;
- (v) if it is possible to correlate definitively either the Main Reef, Main Reef Leader, or South Reef of the Central Rand with the Main Reef Leader of the East Rand;
- (vi) whether it is possible, from mineralogical and petrological data, to make predictions as to the ultimate extent of known reef horizons, and whether this data can be used as an aid in suggesting areas of previously unsuspected payable conglomerates;
- (vii) whether a satisfactory means of reef correlation by mineralogical methods can be devised;
- (viii) whether mineralogical studies on a microscopic scale of a particular reef support sedimentological observations on a macroscopic scale; and
- (ix) whether any mineralogical features observed during the course of the investigation could be used in helping to decipher the origin of some of the more problematic minerals within the banket.

C. BRIEF REVIEW OF PREVIOUS PERTINENT WORK

Much of the literature dealing with the mineralogy of the Witwatersrand banket is of a descriptive nature. The apparent similarity of reef mineralogy from one horizon to another has, in the past, discouraged a comprehensive description of the mineralogy of all the reefs. The detailed mineralogy of a particular reef on a particular mine is frequently well known, but no account exists of the nature of, and variation in, the mineralogy of the same reef on a regional scale.

For many years the standard reference on the subject of basket mineralogy has been the work of Young (1917), who presented a large amount of data, gleaned mainly from the results of thin-section study. Excellent accounts of the ore mineralogy of the basket have been given in more recent publications by Liebenberg (1955) and Ramdohr (1959). Prior to these two publications, no detailed information was available concerning the ore mineralogy of the basket, except for material contained in various publications dealing with a specific aspect of the ore mineralogy. Mendelssohn (1933 and 1944) described secondary minerals in sulphide veins from the East Rand. Jones (1937 - 38) noted an occurrence of cobaltite from the East Rand, and Pelletier (1940) studied pyrrhotite and other sulphides within the basket. Numerous papers describing basket concentrates, mainly from the extraction metallurgist's point of view, have been presented.

D. METHODS OF STUDY

A systematic study was undertaken of all the minerals present in 200 thin-sections examined. In a number of cases, more than one thin-section was cut of a particular sample. Special attention was given to the mode of origin and paragenesis of the more problematic minerals. Photomicrographs were taken to illustrate certain textural relationships of various minerals, and to elaborate on the various forms of the minerals. Thin-sections of selected pebble types were made, and the mineralogy described.

A study was made of 120 polished-sections. Where interesting features existed, more than one section was made of the particular specimen. Some attention was given to the genetic significance of the ore minerals. Numerous photomicrographs were taken to illustrate textural relationships of various mineral types, and to demonstrate certain features referred to in the text.

All the heavy minerals studied were observed in situ. Besides thin-sections and polished-sections, use was made of the Leitz Ultrapak attachment.

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Vlakfontein	Vogelstruisbult
Marievale	East Daggafontein
Daggafontein	S.A. Lands
Van Dyk	Geduld
East Geduld	Grootvlei
Modder East	E.R.P.M.
Rose Deep	City Deep
Crown Mines	C.M.R.

Durban Deep
West Rand Cons.
Libanon
Doornfontein

Luipaardsvlei
Venterspost
West Driefontein

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THE QUALITATIVE MINERALOGY OF THE MAIN REEF AND MAIN REEF LEADER

A. CLASSIFICATION OF THE CONGLOMERATE COMPONENTS

Young (1917) found it convenient to divide the various constituents of the basket into three main categories :

- (i) allogenic constituents, comprising the original detrital components introduced at the time of basket deposition, and including pebbles, matrix material, and hypothetical constituents which were presumed to have been such minerals as magnetite, ilmenite, and titanite that were subsequently completely changed to pyrite, leucoxene, etc;
- (ii) authigenic constituents, comprising secondary minerals formed within, or introduced into, the basket after deposition, such as cementing material, alteration products, and introduced substances; and
- (iii) constituents of uncertain origin, such as gold, uranium, and most of the sulphides.

In general, the scheme as described by Young (1917) was adhered to during the present studies. Allogenic and authigenic components are described, and gold, uraninite, and carbon, plus all the sulphides present are described under the heading of "ore minerals". Components of uncertain origin are described under one of the above headings, depending on which is the most appropriate. It has been found convenient to collectively describe particular mineral components from different reefs. Variations in the properties of zircons from one reef to another, for example, are so small that a separate description of the zircons from each reef would result in much repetition. Major differences in reef mineralogy are mentioned, and the paragenetic sequence and genetic significance of the various minerals are discussed.

The minerals observed in the present study, listed in order of abundance, are as follows :

(i) Allogenic Constituents :

1. quartz
2. leucoxene
3. zircon
4. chromite
5. tourmaline
6. apatite
7. rutile

Allogenetic mineral constituents not observed in the present investigation, but previously described from the banket, include diamond, iridosmine, platinum, monazite, garnet, and xenotime.

(ii) Pebbles :

1. vein quartz pebbles
2. chert pebbles
3. quartzite pebbles
4. quartz porphyry pebbles
5. shale pebbles

(iii) Authigenic Constituents :

1. quartz
2. sericite
3. chlorite
4. chloritoid
5. tourmaline
6. rutile (plus anatase)

Authigenic constituents observed by other investigators, but not observed in the present study, include dolomite and calcite.

(iv) Ore Minerals :

1. pyrite
2. pyrrhotite
3. carbon
4. arsenopyrite
5. chalcopyrite
6. uraninite
7. cobaltite
8. gold
9. pentlandite
10. skutterudite - linnaeite
11. gersdorffite
12. galena
13. sphalerite
14. millerite

Ore minerals not identified in the present investigation, but previously described, include tetrahedrite and niccolite.

B. ALLOGENIC CONSTITUENTS OF THE MATRIX

(a) Quartz

Quartz of allogenetic origin is by far the most wide-spread constituent of the matrix, as would be expected from the generally arenaceous character of the reef horizons studied. In most cases, the sand fraction (.0625 - 2.00 mm.) constitutes about 65% of the total matrix, whereas the silt fraction (.004 - .0625 mm.), which, at times, is difficult to distinguish from quartz of authigenic origin, constitutes about 15%. The total allogenetic quartz content averages about 80%. Small variations in these figures are apparent, but do not appear to be of any significance. Plate 1 shows typical allogenetic quartz grains of the sand grade set in a matrix consisting mainly of silt.

Allogenic quartz particles within the sand range are conspicuous in some parts of the Black Bar, and especially in the Jeppestown shale. Individual grains are often angular and are commonly set in a mass of phyllosilicates. These phyllosilicates usually consist of sericite and chlorite, giving the rock the appearance of a sub-greywacke.

Most of the quartz in the sand grade appears to be of the vein quartz variety, with occasional grains of chert being conspicuous. Strain phenomena, in the form of strain shadows and undulose extinction, are common, and a number of grains may exhibit abrupt discontinuities in optical orientation, which feature is possibly due to rupture. Lines of pores and minute stringers of aligned foreign material may be prominent in some grains, and their general alignment in a number of neighbouring grains suggests that they are products of stress inherited after deposition. In most sections, the original grain boundary is visible in at least some of the particles, and close inspection reveals that the original grains were rounded to subangular. Grain boundaries are more clearly discernible if the matrix contains abundant chlorite. In many cases, especially where the pressure field was more intense, individual grains are extensively fractured, and are often surrounded by quartz of authigenic origin.

The size of sand particles varies greatly from one locality of a particular reef to another, and the size of quartz grains within footwall horizons is usually smaller than the size of quartz grains in the overlying reef. The amount of silt-sized particles in a particular sample varies widely from area to area. Study of this component of the matrix is often made difficult by the fact that extensive recrystallization and migration of quartz, for the most part derived from the silt fraction, have taken place. In some instances, the silt fraction may be composed of a mosaic of interlocking grains and this, together with small flakes of sericite and chlorite, often make the recognition of individual grains extremely difficult.

Replacement of allogenic quartz by sulphide, mainly of the crystalline pyrite variety, is very conspicuous in places. The pyrite crystals occur in a haphazard manner and pay no heed to sand grain boundaries (see Plate 2). In some cases, remnants of the replaced quartz are left behind within the enclosing sulphide, giving the pyrite crystal a porous appearance (see Plate 2). Later corrosion of the secondary pyrite crystals may take place. A common occurrence, where allogenic quartz grains are in close proximity to pyrite, is the outgrowth of fibrous quartz (see under description of secondary quartz) towards the sulphide (see Plate 14). This secondary fibrous, or columnar, quartz is in optical continuity with the parent allogenic quartz grain.

(b) Leucoxene

Leucoxene is one of the most conspicuous accessory minerals occurring in the matrix, and was observed in every sample studied. Notwithstanding this, its distribution, as far as volume is concerned, is very variable, probably because of its diverse origin. Small variations in the relative percentage of the mineral, as compared to chromite and zircon, are apparent from reef to reef, and within particular reef horizons. Specific zones in certain parts of the reefs studied contain exceptional concentrations of heavy minerals. These zones are often extremely leucoxenic, and give to the reef a distinct orange-yellow colour in hand specimens. Microscopic investigation shows that remobilization of the leucoxene has taken place on a large scale, and that numerous grains of zircon and chromite are set in a mass of this material. In other cases, thin films of leucoxene coat authigenic constituents, such as chlorite.

Small, scattered flakes of leucoxene are common in the Black Bar and in the footwall shale of the Main Reef Leader (East Rand), and are usually associated with small amounts of pyrite. Leucoxenic material is often conspicuous along footwall contacts, imparting a yellowish colour to these parts of the reef, if sufficiently concentrated. The frequent association of rounded leucoxene grains with other heavy mineral components

along footwall contacts, especially in the Main Reef Leader and the Main Reef Leader (East Rand) is often distinctive. The footwall quartzite of the Main Reef usually contains scattered grains of the mineral.

It is apparent that, in its present form, leucoxene is the alteration product of an original, rounded, detrital mineral. Close examination of individual grains reveals yellow leucoxenic rims surrounding dark, opaque to highly birefringent cores, probably representing the original mineral.

In thin-section, with ordinary light, leucoxene is opaque and black, often with a brownish to dark green tinge. In reflected light, colours in section are typically orange to yellow. Colour variations are, however, apparent and some individuals are greyish-black in ordinary light and whitish to cream in colour in reflected light. These colour changes possibly represent changes in composition, and the whitish- to cream-coloured variety, which is less abundant, is probably derived from ilmenite. X-ray analysis of leucoxene masses from the Main Reef Leader indicates that it is composed mainly of rutile and quartz, possibly with some hematite. Close examination of grains often reveals minute rutile needles. Under reflected light in polished-sections, the mineral is seen to occur in rounded to irregular, porous and compact masses. The rutile component gives typical strong internal reflections, and the surrounding material often exhibits cloudy white internal reflection. These effects give the grains a strong differential anisotropic appearance with polarised light.

As in the case of associated heavy mineral components, the size of individual grains varies greatly from place to place. In some instances, large oval masses (over 2.00 mm. across) are conspicuous, but the average size is considerably less than this. Rounded masses of leucoxene, both spherical and oval in shape, are most commonly met with, and there is little doubt that the original mineral underwent abrasion prior to deposition. In most cases, however, clues to the original nature and composition of these rounded grains are effectively masked, due to the fact that the shape of the grain has been destroyed by mobilization of the leucoxene. This mobilized product is often seen surrounding original alloigenic constituents, and the shape of such masses is completely irregular. In Plate 27 the diffuse nature of the outline of a leucoxene grain can be seen.

In a number of cases, the cores of grains have been extensively or completely replaced. The dominant replacement minerals are sericite and quartz, the former often containing minute needles of rutile. The effect of replacement is often well seen in polished-sections, where a ring of leucoxene (consisting mainly of rutile) is the only indication of the original grain. Due to its loose knit and often porous structure, the mineral is liable to replacement by ore minerals. Secondary pyrite is often seen replacing grains, and in some cases gold occupies the porous core area (see Plate 58). In samples rich in uraninite, extensive replacement of leucoxene by secondary uraninite may be conspicuous. Particular grains may become almost entirely uraniferous. This type of individual is difficult to distinguish from a radioactive variety of leucoxene.

To decipher the nature of the original mineral, or minerals, which gave rise to the leucoxene, is a problem. Indications are that a number of titanium-bearing minerals were responsible. Skeletal remains of the unmixed portion of titan magnetite occur fairly frequently in the samples studied. The only remains of the original mineral are delicate networks of rutile formed from the ilmenite portion of the magnetite (see Plate 3). These delicate structures, which may be lost in the polishing process, are characterised by three sets of crystallographic directions at about 60° to each other, giving a type of Wiedmanstettan effect. The original iron-rich portion of the titan magnetite has been lost, and probably occurs in the form of pyrite. In some samples, the delicate rutile skeletons are closely associated with abundant, minute flakes of pyrrhotite, which could represent part of the original magnetite fraction.

In a number of cases, beautifully preserved wedge-shaped leucoxene pseudomorphs were observed in pebbles. It seems likely that, in these cases, the original mineral could have been sphene, which underwent no abrasion prior to deposition, due to the protection of the pebble. It is therefore likely that some of the rounded leucoxene grains occurring in the matrix could have been derived from sphene. The acute rhombic cross-sections, or wedge-shaped crystals, are characteristic of sphene, and Liebenberg (1955) has described similar pseudomorphs. This author has also mentioned the occurrence of a radioactive leucoxene, entertaining the possibility of the original mineral having been uraniferous titanite. This type of leucoxene was not identified positively in the present investigation, but some of the material closely associated with secondary uraninite is probably radioactive.

(c) Zircon

Zircon is the most widespread heavy mineral, of undoubted detrital origin, occurring in the reefs studied. A few grains were observed in most thin-sections examined, and certain slides, representing areas of reef particularly rich in zircon, contained up to 25 individual grains in an area of about three square centimeters, which was the average area of thin-sections examined. Concentration of zircon grains, together with other heavy minerals, is often conspicuous along footwall contacts. Zircon grains were observed in the footwall shales of the Main Reef Leader and the Main Reef Leader (East Rand). The mineral was, however, rarely seen in the footwall quartzite of the Main Reef.

In thin-section, grains are usually pale pink to grey in colour, with high birefringence. Individuals studied by Ultrapak illumination, as well as those from crushed samples, show a wide range of colour, varying from colourless, through whitish, to pale yellow, pale pink, deep pink, wine red, and reddish-brown. Well over 90% of the individuals seen were coloured various shades of pink, and no attempt was made to subdivide zircons according to colour. Secondary crystalline outgrowths of authigenic zircon on original detrital grains appear to be rare. Where such growths do occur, the new material is often lighter in colour than the parent grain.

One of the most striking characteristics of the mineral is the well-developed zoning which is seen in many grains (see Plate 4). The phenomenon is best seen in polished-section, and the variability of reflectivity of the various zones is generally marked, an observation also made by Ramdohr (1959). Study of zircons in the present investigation has led to the conclusion that succeeding zones probably have a slightly different composition to the preceding zone. This contention is supported by the fact that some grains contain zones which are of a radioactive nature (probably uraniferous), and numerous specks of a white sulphide, which, according to Liebenberg (1955), is galena of radiogenic origin (see Plate 5). The radioactive portion is usually much softer than the rest of the grain, and is identified by its low relief and by numerous small inclusions of galena. The positions of these radioactive zones is variable. In some cases, most of the grain is uraniferous, and these individuals are very similar in appearance to uraninite. In other cases, the radioactive zone occurs between the outer edge and the inner core (as in the case of the grain depicted in Plate 5). Other individuals have a central uraniferous core. Some finely-zoned grains may contain alternating zones of radioactive and non-radioactive material. According to Liebenberg (1955), the radioactive zircons contain uranium, yttrium, and other rare elements, and are of the cyrtolite variety which is related to malacon.

The size of individual grains fluctuates considerably within a particular sample, and the average size of a number of grains varies extensively from one area of a particular reef to the next. Variations in the length to breadth ratio of zircon grains (giving a rough measure of sphericity) are much less obvious than variations in size. The zircons present in the footwall shales mentioned above are invariably smaller than

those in the overlying reef. The median grain size of these individuals (maximum horizontal intercepts measured) in the footwall shale at East Geduld is .117 mm., whereas the size of zircons occurring in the overlying reef is .160 mm.

Zircon occurs almost exclusively in the form of elongated prisms with well-rounded pyramidal terminations (Plate 6 shows a typical zircon grain occurring within the fine-grained matrix). Individual grains are often extensively fractured in situ, and in some cases component parts have moved away from the parent grain, and constitute discrete particles with a high degree of angularity, and which are disorientated with respect to the parent grain. Small angular zircons, often observed in the matrix, are probably the result of similar fracturing prior to, or just after, deposition.

Zircon grains occur almost exclusively in the fine-grained matrix where they are characteristically surrounded by silty material, sericite, chlorite, and sometimes chloritoid. Fissures within fractured grains are often filled with phyllosilicates, sulphides, and, in rare cases, small hair-like veinlets of gold. Leucoxene may be intimately associated with the fractured grains, and has probably been derived from some pre-existing substance which filled the fissures.

All stages in the moulding of crystal pyrite on zircon have been observed. In many cases, the whole grain has been enveloped by sulphide, and the original rounded grain outlines are sometimes perfectly preserved within the mould (see Plate 7). In other cases, the shape of the surrounding sulphide is a reflection of the shape of the enclosed zircon grain.

Zircon crystals within quartz pebbles are occasionally met with. These individuals show no signs of abrasion, and occur in the usual form of tetragonal prisms with bipyramidal terminations (see Plate 4). These grains differ markedly from their counterparts within the surrounding matrix, the latter individuals being well-rounded due to prolonged sedimentary processes. The zircons occurring within pebbles, which tend to be on the small side, probably reached their present position within the host pebble. Corrosion of the crystal edges of these individuals is fairly common (see Plate 4).

(d) Chromite

Chromite, although widely distributed in the reefs studied, is not as persistent in its occurrence as zircon. It is generally subordinate to zircon in the Main Reef and Main Reef Leader, but occurs to about the same extent as zircon in the Main Reef Leader (East Rand). As in the case of zircon, there is a decided tendency for the mineral to be concentrated along footwall contacts, together with other heavy minerals. Small grains of chromite are sometimes conspicuous in footwall horizons, but in most cases the mineral is almost entirely absent.

Most of the chromite examined exhibits typical optical characteristics in thin-section, i.e. opaque grains with a translucent brown border which is isotropic in polarized light. In a few sections, notably from the Main Reef Leader (East Rand) and the Main Reef (West Wits Line), chrome spinel (picotite) was recognized. The reddish to yellow translucent colour of this mineral is distinctive in thin-section. Chrome spinel has been recognized by Ramdohr (1959) in polished-section, on the basis of reflectivity. The same author has also recognized spinel, but this mineral was not observed in the present investigation.

The size of individual grains within a particular sample, as well as the average size of chromite grains, varies considerably from one part of a particular reef to another. As the mineral crystallizes in the cubic system, most of the detrital particles tend to be spherical in shape, although oval grains are often seen. Individual grains within the matrix are generally well rounded, but in some instances the remnants of crystal outlines

are discernible. Extensive fracturing of chromite grains, in common with other hard alloogenetic minerals, is often very apparent (see Plate 8), and sharp jagged remnants derived from such individuals may be abundant.

The fissures formed as a result of the fracturing mentioned above are commonly filled with an interlocking mass of small sericite flakes which, by their disposition, tend to delineate the original grain boundary (see Plate 8). Less commonly, the fractures are filled with chlorite (see Plate 23) and, more rarely, pyrite and quartz.

(e) Tourmaline

Detrital grains of tourmaline are rare in the matrix of the reefs studied, but some individuals showing the undoubted effects of abrasion do occur. In some instances, a few grains may be seen associated with other heavy mineral constituents. A limited number of grains, probably of alloogenetic origin, occurs in the footwall shales examined.

The colour of the detrital tourmaline examined is usually grass green and bluish-black, with marked pleochroism and birefringence, and it is likely that most of the grains are of the schorl or iron-rich variety. Alloogenetic grains are usually larger in size than the authigenic crystals to be described later. Some of the larger, stubby authigenic crystals observed may represent outgrowths on original detrital grains, the identity of which has been lost. The alloogenetic grains, which are often darker in colour and contain more inclusions than the relatively more abundant authigenic material, are often characterized by outgrowths of the latter material. These outgrowths are almost invariably in optical continuity with the detrital grain, and grow parallel to the c-axis thereof, giving the grain a jagged or frayed appearance. In some cases, the original rounded surface of the detrital grain is faintly discernible (see Plate 9).

Small, well-formed crystals of tourmaline, as well as radiating elongated forms, may be relatively abundant in some quartz grains and pebbles. Some of these individuals have undoubtedly been brought into the conglomerate within the pebble or grain, whereas others are probably of authigenic origin.

(f) Apatite

Alloogenetic grains of apatite are very rare in the matrix, and occur in a very small proportion of sections examined. Small crystals may be present in quartz grains and pebbles. Detrital grains are usually elongated, the terminations often showing signs of abrasion. Fracturing is frequently met with, the fissures commonly being filled with phyllosilicates and sometimes sulphide (see Plate 10). The detrital grains of the matrix are usually much larger than the small, well-formed crystals which are unusually common in quartz pebbles.

(g) Rutile

Rutile of alloogenetic origin appears to be a very rare component of the matrix, and was not identified with certainty in the present study. Leucoxenic alteration has probably affected most of the original detrital grains.

C. PEBBLES

(a) Vein Quartz Pebbles

Pebbles of vein quartz material are by far the most abundant constituents of

the conglomerates examined. These pebbles represent a number of varieties, the most common being milky white quartz. Other varieties include grey and grey-mottled pebbles, jet black pebbles, white vein quartz pebbles with black rims, and clear transparent pebbles. Blue opalescent granules and small pebbles are sometimes conspicuous. The vein quartz pebbles exhibit a number of forms which are common in many quartz veins. Pebbles are often coarsely granular, with individual irregular components varying from roughly equidimensional to components of varying sizes. Irregular, hair-like veinlets, often filled with phyllosilicates, are sometimes common. A coarsely granular texture of irregular masses forming a type of mosaic of sub-parallel recrystallized aggregates is commonly met with, and indicates that much of the quartz has undergone recrystallization (see Plate 11). In many instances, the whole pebble has undergone recrystallization, but in other cases recrystallization has taken place within particular zones in the pebble. Fracturing, which is common in some areas, may give the pebble the appearance of being recrystallized. Some individuals have probably undergone no recrystallization, and in such cases the pebble is composed of homogeneous quartz with no optical irregularities.

Colour changes between the various quartz pebbles are probably due to minute inclusions of foreign material which absorb light and produce darker tones. Some of these inclusions may be in the form of minute magnetite and rutile crystals, while others are of carbon. Strain surfaces probably also influence the colour of quartz pebbles.

The size of pebbles is variable, ranging from granules up to individuals three inches across. Pebbles of the latter dimensions were observed in the Main Reef Leader only. The size of individuals within a particular reef horizon is generally very variable.

Pebbles contain a variety of mineral inclusions, the most common being zircon (see Plate 4), apatite, and tourmaline. In some cases, pebbles may contain inclusions of chlorite which is completely different to the chlorite occurring in the surrounding matrix. In a number of cases, minute veins containing mainly sericite flakes, and, less often, small chlorite crystals, are seen cutting through pebbles. It appears as though strain surfaces within vein quartz pebbles have acted as channelways for this material. The absorption of light by these fractures could cause the dark and mottled appearance of some of the pebbles.

(b) Quartzite Pebbles

Quartzite pebbles are generally of minor importance in the reefs studied. The quartzite is usually very different to the quartzites occurring within the Witwatersrand System. Recrystallization is generally apparent, and matrix material is sometimes almost entirely lacking. The recrystallization usually gives rise to an irregular mosaic texture of equi-sized units. These units are the main criteria for distinguishing quartzite pebbles from pebbles of recrystallized vein quartz, which generally contain units of varying sizes. In some cases, the sizes of the individual particles are variable, and it is very difficult to distinguish this variety of pebble from pebbles of vein quartz.

(c) Chert Pebbles

Chert pebbles are usually conspicuous in the conglomerates examined. Unbanded individuals vary from grey to brown to yellow to black in colour, and are usually fairly spherical. Banded cherts may be conspicuous in many places. The unbanded chert pebbles consist of a homogeneous aggregate of equidimensional grains which form a kind of mosaic. Microscopic examination reveals that the banded effect is the result of layers of coarser and finer material. In many cases, the banding is accentuated by, or entirely the result of, one or a number of the following factors : (i) layers containing dark

material, possibly in the form of hematite (see Plate 12); (ii) general staining of particular areas of the pebble; (iii) zones containing abundant phyllosilicates, generally in the form of chlorite and sericite; (iv) zones containing abundant sulphide, usually in the form of well-developed pyrite cubes, which appear to have preferentially replaced certain parts of the pebbles; and (v) zones containing minute grains of magnetite with some rutile needles.

In some cases, recrystallization of chert pebbles in contact with matrix material has taken place, giving the pebble a coarser-grained appearance in this contact area.

(d) Quartz Porphyry Pebbles

Quartz porphyry pebbles are generally of minor importance in the reefs studied, and are conspicuous only in a few areas. Such pebbles were observed in the Main Reef Leader (East Rand), especially in samples from Modder East, and in the Main Reef from the West Rand area. The pebbles are usually grey in colour, and contain conspicuous phenocrysts set in a very fine-grained, altered, compact groundmass. The phenocrysts are generally composed of quartz, and are fairly angular (see Plate 13). Most of the phenocrysts, however, show the effects of corrosion characteristic of quartz porphyries to a varying extent, and in some cases the edges of the original phenocrysts have been well-rounded. The groundmass is generally composed of abundant quartz, associated with a large amount of sericite. Much of this sericite has undoubtedly been derived from the decomposition of original felspar, but no felspar was noted in the samples examined. According to Young (1917), the quartz porphyries have undergone silicification, with the production of sericite.

(e) Schist Pebbles

Schist pebbles are very erratically distributed, and are often found in reef overlying clay footwalls. Pebbles of 'schist' are most commonly met with in the Main Reef Leader and the Main Reef Leader (East Rand). A few schist pebbles which could have been derived from basement rocks were noted in the Main Reef Leader (East Rand).

Microscopic examination reveals that the mineralogy of the pebbles occurring in the Main Reef Leader is identical to that of the Black Bar, being composed of a mass of chloritoid crystals, together with chlorite, sericite, and quartz. In this respect, they are similar to the rounded chloritoid bodies described by Young (1917) in the Main Reef Leader. Most of the schist pebbles of the Main Reef Leader (East Rand) are mineralogically similar to the underlying Jeppestown shale, being composed, for the most part, of chloritic and sericitic material. The pebbles are of average size, with respect to the other varieties of pebbles occurring in the same portion of reef, usually being irregular in shape. They have no definite borders, and chloritoid crystals from the pebble are seen penetrating matrix material in the case of pebbles in the Main Reef Leader. This indicates that the growth of chloritoid has taken place after the deposition of the pebbles, during a period of metamorphism.

From the above, it would seem likely that most of the schist pebbles, referring particularly to those in the Main Reef Leader and Main Reef Leader (East Rand), have been derived from the underlying clay footwall horizons. It is probable that at the time of reef deposition small particles of semi-consolidated clay were incorporated in the reef material as irregular blebs or as interstitial mud. The disposition of some of the vein quartz pebbles lying directly on the Black Bar, for example, seems to suggest that the latter material was in a semi-consolidated condition at the time of reef deposition.

In addition to the 'schist' pebbles described above, there is another variety of schist pebble, very rarely encountered, which was probably brought into the basin of

deposition together with the more common vein quartz and chert pebbles. These pebbles appear to have been derived from basic schists and are composed mainly of chloritic material.

D. AUTHIGENIC CONSTITUENTS OF THE MATRIX

(a) Normal Quartz

Quartz of a secondary nature occurs very abundantly in the conglomerates studied, and is the most important authigenic component of the matrix in many cases. It has been largely responsible for the cementation of the blanket, and much of the lithification has been brought about by the precipitation of this material in suitable pore spaces. Authigenic quartz does not occur to the same extent in footwall shales as it does in the reef horizons. However, it might be the chief cementing material in the footwall quartzite of the Main Reef.

In the Main Reef and Main Reef Leader it occurs most commonly as overgrowths on allogenic quartz grains. The growths are almost invariably in optical continuity with the parent sand grain, and the original rounded edges of the latter grains are visible with normal light, often being demarcated by a thin, discontinuous line of foreign material. If the allogenic grains are close together, the authigenic rims of neighbouring grains merge with each other, giving the effect of a mosaic with irregular edges. If, as often happens, the original grains are separated by relatively large areas of fine-grained silty material, authigenic quartz rims of the larger particles do not merge to form a mosaic. In some instances, authigenic rims around original grains may be entirely lacking, especially if the matrix contains abundant ferro-magnesian minerals. In such cases, original grain boundaries are clearly visible.

It is apparent that the authigenic quartz formed relatively late in the history of the blanket. In many instances, it is seen replacing phyllosilicates, such as chloritoid, and, in some cases, chlorite. A large amount of the material has undoubtedly originated from slight solution of the fine-grained silty material within the matrix, which was susceptible to mobilization. Replacement phenomena, as well as clay mineral diagenesis, were probably also sources of authigenic quartz.

(b) Columnar or Foliated Quartz

Closely allied to the authigenic quartz described above, but occurring in a completely different fashion are the columnar aggregates of quartz (see Plate 14), which were first described by Young (1917). This type of authigenic quartz is not as widespread in its distribution as the normal variety. It is very well-developed in the Main Reef Leader (East Rand) where it often appears to be associated with portions of reef rich in pyrrhotite or pyrite. The occurrence of columnar quartz, although conspicuous in isolated areas, is generally of minor importance in the Main Reef and Main Reef Leader. Its close association with pyrite grains or similar resistant minerals, such as chromite, is noteworthy, and Young (1917) attributed its growth on pyrite to contraction and fracturing of the pyrite grain. Authigenic columnar quartz was not noted in any of the footwall horizons examined. The general alignment of the material within a particular sample is distinctive, and has a direct bearing on its origin. This alignment implies some type of structural control, and it appears that the columnar nature of the quartz has resulted from its growth in pressure shadows. These shadows are invariably in the direction of schistosity, and appear on one or both ends of pyrite crystals or granules (see Plate 15), and not infrequently as narrow fringes surrounding the whole grain.

Pabst (1931) studied the formation of pressure shadows in a sequence of rocks consisting mainly of slates. Even those rocks which did not lend themselves to the

development of slates, such as conglomerates, showed a marked schistosity and stretching under suitable conditions of stress. According to Harker (1956), crenulation folds are formed if the whole mass of a rock which has suitable mineralogy, such as a slate, and which suffers continuous deformation, is of the same yielding nature. The development of crenulation folds, or possibly conjugate shear surfaces, in the footwall shales of some areas of the conglomerates studied indicates that some type of stress field was active (see Plate 16). The overlying reef in such cases invariably contains an abundance of pressure shadows which are filled with columnar quartz. If the stress which caused the crenulation folds in the footwall shale was transmitted to the overlying conglomerate, and if this horizon contained hard minerals, the yielding matrix would have tended to flow past the obstruction. The space where the protection of the resistant crystal caused a relief of pressure parallel to the schistosity would have been filled continuously by quartz. If the deposition of quartz took place gradually during differential movement, the opening would eventually have been filled with elongated columns of quartz. It is probable that the solution of quartz took place at right angles to the growth of the columnar quartz. Many allogenic quartz grains show signs of crush with aligned bubble inclusions, indicative of stress, and, according to Pabst (1931), the migration of this quartz to areas of low pressure is easily explained by Riecke's principle.

Macroscopically, slickensided pebble sockets, often coated with sulphide, as well as a general foliation of the reef, are good indicators of the occurrence of this type of quartz on a microscopic scale.

The quartz filling pressure shadows occurs in the form of flames or columns, closely associated with grains of sulphide (see Plate 14). In most instances, numerous columns are present, but, in the case of small pyrite grains, only one column, representing a single crystal, may be present. Generally speaking, the columns are roughly parallel (see Plate 14), but may tend to radiate out from the sulphide nucleus. The width of the columnar growths depends to some extent on the available surface of sulphide, or other resistant material, and accordingly may vary considerably. Bending of the columns (see Plate 14) is probably due to differential lateral compression during growth. One of the most striking features of the columnar quartz is its very clean nature, with an almost complete lack of foreign inclusions (see Plate 17). The same photograph shows the impure state of the surrounding matrix material. Striking features are the sharp contact of columnar quartz with pyrite surfaces, and the development of a more profuse growth in the vicinity of the pyrite edge. The almost invariable gradation of this type of quartz into pebble quartz or quartzose parts of the matrix is marked (see Plate 14). In most cases, the individual columns are intimately associated with similar, usually narrower, columns of either sericite or chlorite.

Columnar quartz, similar in some respects to the variety described above, and which is well-developed in the Main Reef Leader (East Rand), occurs essentially in the silty matrix, of which it appears to be a slightly remobilized product. Unlike the true columnar quartz, it is closely associated with, and grows from, allogenic quartz grains, instead of from a sulphide or other hard mineral component. It is usually orientated parallel to the variety described above, and was probably formed in the same stress field responsible for the formation of the latter. This variety is always associated with abundant phyllosilicates (dominantly sericite which may, or may not, be aligned in a parallel fashion), giving it a 'dirty' appearance. The contrast between the two varieties is demonstrated in Plate 17.

In all cases, pyrite or some other hard mineral is a prerequisite for the growth of true columnar quartz in pressure shadows. Besides the columnar quartz developed in the pressure shadows caused by the occurrence of random resistant grains within the matrix, columnar quartz may be extensively developed in minute fractures within rounded pyrite nodules (see Plate 18). This quartz invariably grows at right

angles to the walls of the opening, and there is no alignment with the general growth direction of columnar quartz in the surrounding matrix. Pabst (1931), after measurement of the optic orientation of similar quartz, came to the conclusion that the long axes of the grains are at right angles to the controlling pyrite face, whatever its attitude with respect to the schistosity of the enclosing rock. The size of the individual columns of quartz within narrow veins similar to those described varies from about .007 mm. to about .10 mm.

In some places, sulphides show a definite alignment with the recrystallized columns of silty material referred to above (see Plate 19). The sulphide (in this case pyrrhotite) is aligned at right angles to the stress direction, and the disposition of the mineral would seem to suggest that its elongated form may be due to the stress which produced the general schistosity in the rock. Close examination reveals that small columns of quartz grow at right angles to the sulphide immediately adjacent to the surface of the mineral.

Chlorite and sericite, as mentioned, are commonly observed growing parallel to columnar quartz in pressure shadows. In rare cases, a large proportion of a particular pressure shadow may be composed of sericite growing in a typical columnar fashion. Chlorite, in bands alternating with quartz, is a more common associate, however. In other cases, the chlorite tends to form a solid mass within the shadow. Where the matrix is particularly rich in chlorite, pressure shadows may be composed entirely of this mineral. It usually occurs in the form of oval-shaped lobes which are characteristically set on either end of pyrite grains, at right angles to the stress direction.

Most of the quartz filling the pressure shadows has presumably been derived from the solution of nearby alloigenic grains under stress, and its formation would appear to be late in the sequence of authigenic mineral paragenesis.

(c) Sericite

After quartz, sericite is generally the most abundant authigenic mineral within the matrix. However, the sericite content in a particular reef horizon is very variable. In some cases, especially in the Main Reef Leader (East Rand), it is the only phyllosilicate present. In other instances, it may be almost entirely absent. Sericite is a common constituent of the footwall Jeppestown shale in the East Rand, and is often associated with abundant chlorite. Some large masses may occur in the Black Bar, but sericite is generally of minor importance in this horizon. The mineral is almost invariably present in the footwall quartzites of the Main Reef.

Microscopically, sericite is indistinguishable from pyrophyllite, which Fuller (1958) has shown to be a widespread component of the Upper Division of the Witwatersrand System, and to be particularly characteristic of the Main-Bird Series. Some of the larger sheaths occurring within the matrix and coating slickensided surfaces are probably pyrophyllite. The material in fractures within the rock possibly represents the result of some kind of hydrothermal activity. Field and laboratory evidence indicates that the mineral is produced by the hydrothermal alteration of fine-grained quartz-felspathic rocks at moderate depths, and at temperatures in the vicinity of 400°C. Its formation is accompanied by the breakdown of felspars, silification, and the leaching of alkalies. It is probable that most of the pyrophyllite, as well as the sericite, has recrystallized from original alloigenic components, rather than from hydrothermal solutions. Some of the sericitic material has, in addition, undoubtedly been derived from the alteration of felspar.

The size of individual particles is very variable, from small flakes about .003 mm. in length to large compact masses up to 1 mm. in length. The shape of the aggregates is often determined by the surrounding quartz grains. Thus, large, broad sheaths of sericite, as well as narrower bands, are often seen conformably following the borders of sand grains

and pebbles, irrespective of the general 'schistosity' of the matrix. Probably the most common mode of occurrence of sericite is in the form of small flakes, usually occurring as a disorientated network. Small flakes within the silty part of the matrix may form a rough grid pattern, with scattered flakes growing more or less at right angles to each other. Pressure shadows completely filled with sericite are sometimes present.

The mineral is commonly intimately associated with quartz of both the authigenic and alloigenic varieties. It frequently occurs in elongated slivers aligned parallel to elongated masses of regenerated silty material. The mineral is often seen extensively replacing the edges of sand grains within the matrix, obliterating the original edges of these grains. The parallel growth of elongated sericite flakes with authigenic quartz in pressure shadows is sometimes conspicuous. Sericite, together with small flakes of chlorite, may constitute most of the matrix in particular areas. This type of association often gives the matrix a matted appearance, in which small elongated crystals of rutile may be conspicuous. Elongated flakes of sericite sometimes occur parallel to elongated chlorite crystals, either in the matrix or in pressure shadows (see Plate 22). The mineral may be associated with minute black specks which can occur in great abundance. This material is sometimes leucoxenic, and probably represents rutile, but in other cases the identity is uncertain. Minute rutile needles are generally characteristic of areas rich in sericite. In many places, sheaths of sericite are parallel to the crystal faces of pyrite. This sericite often separates the sulphide from either chlorite or chloritoid. Replacement of fractured minerals by sericite along fissures is sometimes marked, and fractured, rounded pyrite grains are particularly susceptible (see Plate 20), as are other fractured heavy mineral components (see Plate 8).

According to Young (1917), a large proportion of the sericite has been precipitated from solutions which entered the rock from outside, while a smaller proportion is probably derived from original felspathic material. From its widespread occurrence in the reefs studied, it seems probable that most of the sericite, and much of the other phyllosilicates have been derived from the re-organization of interstitial mud within the matrix. It is thought that the mineral was one of the last phyllosilicates to crystallize (together with chlorite) under conditions of stress.

(d) Common Chlorite

Chlorite is not as widely distributed as sericite in the reefs studied, but may be abundant in some areas where it can constitute up to 100% of the phyllosilicates. In other areas, its total absence is distinctive. The mineral occurs in both the Main Reef and Main Reef Leader (especially in the E.R.P.M. and Rose Deep area). Chlorite, together with sericite, is widely distributed in the footwall Jeppestown shale of the Main Reef Leader (East Rand). In the Black Bar footwall of the Main Reef Leader, it is subordinate to chloritoid. The mineral was not observed in the footwall quartzite of the Main Reef in the West Rand area. No samples of Main Reef footwall quartzites were available from other areas.

The composition of the chlorite occurring within the matrix varies a great deal, as is evidenced by colour and other optical properties. No attempt was made to identify individual members of the chlorite family, although most of the material studied apparently belongs to the orthochlorite group which is relatively free of iron. Of this group, the variety penninite occurs most commonly, as judged by its characteristic anomalous Berlin-blue interference colour. The birefringence of the chlorite examined varies greatly, and this property is possibly a sensitive indicator of the iron magnesium ratio of the mineral. Pleochroism is generally marked, from yellow or light brown to green, and strong absorption may be apparent. Cleavage may be well marked, especially in the radiating bunches of larger crystals, where it is characteristically parallel to the 001 crystallographic direction (see Plate 21). Staining of chlorite by zircon and chromite grains and by carbon nodules is fairly common, and the chlorite in the immediate vicinity

of such grains often has a yellow colour.

The size of individual crystals or masses is hard to determine because of the various forms which the mineral assumes. Chlorite occurs irregularly distributed throughout the matrix, typically as aggregates of fine scales or as individual scales. The mineral, by virtue of its freer solubility, often tends to gather into patches and knots, and larger distinct individuals displaying a number of forms are frequently met with. These individuals may take the form of large, single, crystalline masses or radiating bunches of crystals (see Plate 21). Large, irregular blobs, as well as compact masses, are also common. In many cases, chlorite occurs as finely-disseminated dark grey to green masses which are possibly a mixture of chlorite and some other mineral, probably carbon. This material may also form large, oval aggregates containing sulphides. These aggregates average .65 mm. in length. Oval masses of homogeneous chlorite are fairly common, and are particularly well developed in pressure shadows.

The mineral is commonly very closely associated with sericite, especially in scaly aggregates where the sericite occurs as minute flakes within masses of chlorite. Also of common occurrence is the parallel intergrowth of sericite and chlorite, often in the form of elongated sheaths which may coat vein walls (see Plate 22). The close association of elongated slivers of chlorite and columnar quartz, filling pressure shadows, has been described earlier.

The occurrence of abundant chlorite with pyrite, where the latter mineral occurs extensively, is well-marked in some places. The mineral is usually distinctly younger than the crystal pyrite, and clearly surrounds the latter constituent. The reverse situation occurs less frequently, where crystal pyrite encloses chlorite. According to Young (1917), the amount and variety of sulphide are often accompanied by an increase in the chlorite content of the matrix in the vicinity of basic intrusions. The abundance of chlorite in conglomerates containing pyrrhotite has often been cited as evidence for the hydrothermal origin of the pyrrhotite and other minerals. In the samples studied in the present investigation, however, there appeared to be no connection between the chlorite content and the occurrence of pyrrhotite.

Chlorite may often extensively replace or invade fractured heavy mineral grains along cracks. Plate 23 shows a fine-grained aggregate of chlorite occupying a crack in a chromite grain which has been pushed apart due to the force exerted during the growth of the chlorite. Pseudomorphous replacement of earlier minerals by chlorite in the samples studied was infrequently seen. Chloritic masses within sericitic material, which on close inspection reveal a clearly discernible six-sided outline, have been observed. These masses could represent the pseudomorphous replacement of an original amphibole, although characteristic cleavage is not apparent. Koen (1962) reported similar occurrences from the East Rand.

A type of chlorite, infrequently met with, occurs as irregular patches within quartz pebbles. It is usually bright green in colour, with strong pleochroism, and shows anomalous blue interference colours. It differs markedly from the chlorite occurring in the surrounding matrix, and was probably brought into the conglomerate within the pebble.

It seems highly probable that most of the chlorite, except that occurring in close proximity to intrusions, is of a metamorphic origin. It can be regarded as "background" chlorite, formed from the reconstitution of interstitial mud which must have existed in the matrix prior to diagenesis. Portions of the matrix very rich in chlorite have probably been influenced by the proximity of dykes or sills, or of hydrothermal veins. It is apparent from microscopic evidence that chlorite was one of the last minerals to crystallize, and it is often seen surrounding chloritoid crystals, as well as other earlier minerals.

(e) Hydrothermal Chlorite

Very narrow, undoubtedly hydrothermal veins, containing chlorite, are occasionally met with. These veins are particularly well-developed in the Pebbleless Bastard Reef on the Rose Deep Mine. The veinlets cut across the matrix material, and in places anastomose, to form a number of branches. Chlorite is abundant in these veinlets, and differs markedly from the chlorite of the matrix, in that it has a distinct pale green colour, as well as marked anomalous blue interference colours. The chlorite of the matrix, by contrast, is of a very dark variety, containing specks of carbon, or an unidentified dark opaque substance, with no marked birefringence. In addition to chlorite, these veins contain large masses of quartz and sulphide, the latter of which is not present in the surrounding matrix. This quartz shows well-developed tension fractures at right angles to the vein wall, and in some areas the veins are cut by a younger generation of veinlets consisting almost entirely of vein quartz.

(f) Chloritoid

Chloritoid is, generally speaking, a widespread mineral in the rocks of the Witwatersrand System. It occurs abundantly in the matrix of the Main Reef and Main Reef Leader, but is entirely absent from the matrix of the Main Reef Leader (East Rand). The following description, therefore, applies only to the Main Reef and Main Reef Leader, both of which carry chloritoid to a variable extent. In some areas, it may constitute up to 80% of the phyllosilicates and up to 12% of the total matrix material, whereas in other areas a few isolated crystals are the only indications of its presence. In common with other shale footwall horizons underlying some of the major reef horizons of the Witwatersrand System, chloritoid is a particularly abundant constituent of the Black Bar. In this horizon, the mineral may constitute over 50% of the total volume of the rock (see Plate 24). The chloritoid occurs in a very similar manner to the chloritoid in the overlying reef, and the contact between the Black Bar and the reef horizon is fairly sharply defined where the profuse development of chloritoid is terminated by crystals of chloritoid projecting into the reef material. The mineral is apparently absent in the Jeppestown shale, which often forms the footwall of the Main Reef Leader (East Rand). Available samples of Main Reef footwall quartzites from parts of the West Rand area contain abundant chloritoid (see Plate 25).

Chloritoid crystals generally occur randomly throughout the matrix, with no apparent orientation, to give the rock a porphyroblastic appearance (see Plate 26). Bigger crystals may be in optical continuity over large areas, giving the crystal a type of coarse poeciloblastic texture. The chloritoid is characterised by high relief. The colour is usually dark green to grey, and pleochroism, although not generally apparent, may be marked in some of the larger individuals, where colour changes from pale blue to green are discernible. The mineral has well-developed prismatic cleavage, and intersections of this cleavage on basal planes give an angle of 60° . Birefringence is very low (generally grey of the first-order). Extinction (the angle varies between 0° and 20°), in many cases, is not complete, because of the very high dispersion of most of the crystals. Polysynthetic twinning is a characteristic feature, and is often helpful in distinguishing individual crystals. The mineral is dominantly optically biaxial positive, although some crystals may give a negative sign.

Chloritoid occurs mainly in the form of elongated, prismatic crystals, with the ratio between the longest and shortest directions remaining fairly constant. The size of individual crystals varies greatly, from over .5 mm. in length to under .1 mm. The following figures represent the longest and shortest axes of individual crystals occurring within the matrix of the Main Reef Leader :

Long Axis	Short Axis	Long Axis	Short Axis
.716 mm.	.194 mm.	.300 mm.	.060 mm.
.566 mm.	.089 mm.	.280 mm.	.060 mm.
.536 mm.	.095 mm.	.270 mm.	.060 mm.
.450 mm.	.090 mm.	.238 mm.	.058 mm.
.387 mm.	.060 mm.	.209 mm.	.045 mm.
.373 mm.	.089 mm.	.194 mm.	.045 mm.
.373 mm.	.060 mm.	.194 mm.	.042 mm.
.358 mm.	.055 mm.	.180 mm.	.040 mm.
.343 mm.	.089 mm.	.175 mm.	.037 mm.
.313 mm.	.075 mm.	.160 mm.	.023 mm.
<u>Average Size</u>		<u>Average Ratio of Long to Short Axis</u>	
<u>Long Axis</u>	<u>Short Axis</u>	4.8 : 1	
.331 mm.	.068 mm.		

Besides the more usual prismatic crystals, chloritoid often tends to occur in rosette-like aggregates which radiate out from a central point or nucleus (see Plate 27). The radii of these rosettes vary, but are usually not very large, and give the appearance of a single crystal of chloritoid with frayed edges (see Plate 28).

Good evidence of the metamorphic origin of chloritoid is afforded by the occurrence of hour-glass structures and foreign inclusions in some crystals. The hour-glass structure is explained by Harker (1956) as due to the force of crystallization causing a growing crystal to brush aside foreign material, but not completely reject it. The result is that trains of inclusions remain caught in the crystal along certain directions in which the force was least effective. This type of structure and the occurrence of foreign inclusions are common in metamorphic minerals, especially in the lower grades. According to Halferdahl (1961), hour-glass structure is also distinctly visible in some chloritoids which are free from inclusions.

Crystalline pyrite surrounding well-formed chloritoid crystals is a fairly common occurrence (see Plate 29). Small fragments of chloritoid are often seen isolated within the enclosing pyrite, and small stringers of vein pyrite, as well as chalcopyrite, are frequently met with, replacing chloritoid along cleavage traces, and intimately associated with the spaces in the framework produced by the radial growths (rosettes) of chloritoid. These phenomena are best observed in polished-section. Well-formed crystals of chloritoid are often enclosed by pyrite of the porous variety (see Plate 26). Chloritoid crystals moulded on pyrite are also present. Of interest is the fact that the latter pyrite is exclusively of the rounded variety (see Plate 27). The replacement of chloritoid by quartz is a very distinctive feature of the samples studied (see Plate 30). In places the effect is slight (see Plate 28), but in other instances most of the crystal may be replaced, and aligned inclusions are the only indication of the original chloritoid. Penetration of quartz along the cleavage planes of the mineral is well marked, giving the edge a jagged appearance which is characteristic of chloritoid undergoing such replacement. Replacement of this nature often proceeds from the central nucleus outwards. This is marked in Plate 30, and the beginning of similar replacement can be seen in Plate 28. Small crystals of rutile and patches of leucoxene are commonly scattered throughout chloritoid crystals.

Chlorite is, in many cases, a common associate of chloritoid, although the almost complete lack of the mineral in samples rich in chloritoid is distinctive in some areas of the Main Reef. When chlorite is closely associated with chloritoid, the latter mineral is invariably surrounded by the chlorite, the chloritoid crystals assuming a porphyroblastic disposition. Sericite, which is often closely associated with chlorite, may often surround, or slightly replace, the edges of chloritoid crystals.

Fairly common in the Main Reef Leader are elongated slivers of greenish-yellow material having the general appearance of pebbles, but with irregular outlines. Microscopic examination reveals that this material is composed of a mass of chloritoid crystals, and is very similar in appearance to Black Bar material. It seems unlikely that it was brought into the reef as a pebble. No definite rounded outlines were observed, and the chloritoid, which is an obvious metamorphic product, penetrates surrounding matrix material. The 'pebbles' occur near the base of the reef, and in some cases are connected to the underlying Black Bar by a long line of disorientated chloritoid crystals. It is contended that this material was derived from the underlying Black Bar at the time of introduction of the conglomerate. Young (1917) has suggested a similar origin for the chloritoid masses occurring in the Main Reef Leader.

It seems probable that the chloritoid in the reefs studied, and in the Witwatersrand System as a whole, is of a metamorphic origin. This is apparent from the wide distribution of the mineral, and its typical porphyroblastic nature. In addition, hour-glass structures observed in some individuals are indicative of metamorphism. Halferdahl (1961) has tabulated the typical mineral assemblages of chloritoid-bearing rocks from all parts of the world. The large majority of rock-types listed by him are metamorphic in origin, and the development of chloritoid by hydrothermal activity appears to be a very localised feature. The most common mineral assemblage in the low-grade chloritoid schists is chloritoid, quartz, chlorite, muscovite, rutile, and iron oxide, an assemblage very similar to that of the reefs under examination. According to Turner and Verhoogen (1960), chloritoid is restricted to the low-grade, or greenschist, facies of metamorphism. A probable range in temperature of 300-500°C, under a water vapour pressure of 3000 to 8000 bars, is given by them for this grade of metamorphism. A high aluminium content is a prerequisite of the formation of the mineral, which has an average Al_2O_3 content of about 40.0% (Halferdahl, 1961). Harker (1956) stated that chloritoid is produced only in rocks which, with an abundance of Al_2O_3 and FeO , are relatively poor in magnesia, lime, and potash. These observations are borne out by Turner and Verhoogen (1960) and Halferdahl (1961), the latter of whom has concluded that little, if any, stress is required for the formation of the mineral. This is in contradiction to the previously held view that some kind of stress is necessary for the formation of the mineral. It appears as though the temperatures at which chloritoid forms are not critical, and the mineral can, therefore, not be employed as an index of the temperature of formation.

It would seem likely from the above that the composition of the original interstitial mud within the matrix was the most critical factor in the formation of the mineral. It is contended that the lack of chloritoid in the Main Reef Leader (East Rand) is a manifestation of the fact that the original composition of the interstitial mud differed from that of similar material in the matrix of the Main Reef and Main Reef Leader horizons. Microscopic examination reveals that chloritoid, by virtue of its porphyroblastic form and association with other minerals, must have been the first phyllosilicate to crystallize, where the composition of the interstitial material was suitable, i.e. a high Al_2O_3 and FeO content. Because the composition of the original material changed with the subtraction of Al_2O_3 and FeO on crystallization of the mineral, or because these compounds were originally not abundant, chlorite and sericite formed in varying proportions which depended on the composition of the interstitial mud.

(g) Tourmaline

Authigenic tourmaline occurs relatively abundantly in the reefs studied, and may be very conspicuous in some samples. Its wide distribution is distinctive. Well-formed authigenic crystals are often much in evidence in footwall shales, and individuals may grow to a considerable size.

Most of the tourmaline occurs in the form of well-developed prismatic crystals within the fine-grained matrix. These crystals are typically greenish to blue in colour, and may sometimes be mistaken for small flakes of chlorite, except that their birefringence and pleochroism are much more marked. Most of the material, unlike the detrital tourmaline, appears to be of the dravite variety, with pleochroism from colourless to yellow to pale green and blue. The material is generally relatively free of inclusions. As mentioned before, authigenic tourmaline growing from detrital grains is usually in optical continuity with the parent grain. The same applies to small authigenic outgrowths from larger individuals of the same material. In some cases, however, these growths may be haphazardly orientated (see Plate 31). It is probable that some of the larger stubby crystals of tourmaline have been derived from original allochthonous grains. The original grains are rarely seen. The size of crystals is very variable, from minute individuals only seen under high-power magnification to large masses. The authigenic crystal shown in Plate 35 has a length of .46 mm. and a width of .16 mm.

Authigenic crystals usually occur in the fine-grained silty matrix, associated with abundant flakes of sericite. There is often a tendency for numerous small tourmaline crystals to be concentrated in small bunches in particular parts of the matrix, and these aggregates could represent the former locations of detrital grains. In some cases, isolated spherical masses of pyrite are associated with tourmaline crystals, where the pyrite appears to surround the tourmaline. Young (1909) has described similar occurrences. The presence of small crystals of tourmaline in quartz pebbles is fairly common.

(h) Rutile

Authigenic rutile is a very widely distributed mineral in the matrix of the reefs studied. Most of the material is closely associated with leucoxenic masses, but discrete crystals of a different origin are plentiful. Small rutile crystals, not associated with leucoxene, may be common in the shaly footwalls of the Main Reef Leader, and the Main Reef Leader (East Rand), and small individuals almost invariably occur in the chloritoid of the Black Bar.

Individual crystals are yellowish to red or brown in colour, and commonly exhibit bipyramidal terminations. Geniculate- or elbow-twinning is sometimes observed. Crystals are often very small, usually being of the order of .03 mm. in length, although much smaller individuals do occur. Large irregular masses within quartz pebbles may be up to .2 mm. across. Well-formed, elongated crystals are sometimes conspicuous, and tend to occur in clusters which may, in places, form a felty mass or network of interlocking needles, known as sagenite. Discrete authigenic crystals within the fine-grained matrix are most commonly associated with sericite, while small rutile crystals often occur within chloritoid crystals. The association of rutile with leucoxene has been discussed earlier. Penetration of needle-like rutile crystals into quartz pebbles is fairly common, and has been suggested as a possible cause of the dark-edged pebbles. In addition, small crystalline individuals may occur scattered throughout quartz pebbles.

E. ORE MINERALS

(a) Pyrite

Pyrite is by far the most abundant sulphide occurring in the three reef horizons studied. In the majority of cases, it constitutes 90%, or more, by volume, of the total ore minerals present, but there are some notable exceptions. It is the dominant ore mineral in all the samples of Main Reef and Main Reef Leader, but may be subordinate to pyrrhotite in some samples of Main Reef Leader (East Rand). Small specks of pyrite are common in the shale footwalls of the Main Reef Leader and Main Reef Leader (East Rand). This pyrite is invariably of the crystalline variety, and no rounded individuals were noted. In some cases, footwall and hangingwall quartzites may be extensively replaced by secondary, or crystalline, pyrite. The mineral occurs in a number of forms which, although related, are of different significance and have distinctive characteristics. Ramdohr (1959) has recognized a number of varieties, and many of these have been observed during the course of the present investigation.

(i) Rounded Pyrite

Rounded grains of pyrite in the matrix first drew attention because of their unusual shape. It is generally acknowledged that pyrite is a mineral with a strong tendency to form crystal outlines, and it is for this reason that Becker (1896) referred to "pyrite pebbles" which were considered by him to be of detrital origin. The term "pebble pyrite" is often taken as being synonymous with the term "buckshot pyrite", a mining term in common use on Witwatersrand mines. For present purposes, any pyrite particle which displays rounded edges has been termed rounded pyrite, in preference to the terms "pebble" or "buckshot" pyrite. The vast majority of rounded pyrite grains are less than 2 mm. in diameter which places them in the sand-grade of sedimentological size classifications. It is suggested that rounded pyrite grains between 2 and 4 mm. be referred to as granular, or buckshot, pyrite, and rounded grains greater than 4 mm. as pebble pyrite. Rounded pyrite grains constitute the bulk of the pyrite in many of the samples studied, and can be conveniently divided into a number of types.

(1) Compact Rounded Pyrite

This variety is by far the most abundant, and usually constitutes 90%, or more, of all rounded grains. It has not been observed in any of the footwall horizons. It seems likely that this pyrite reached its present position in the matrix in the form of undoubted detrital grains, and that little, if any, has been derived from original black sand. Ramdohr (1959) stated that, contrary to present-day thinking, "pyrite is present as indisputably abraded pebbles (in great abundance)". All the pyrite examined is of a typical brass-yellow colour, with high reflectivity. No anisotropic individuals were noted. In a number of cases, irregular spherical forms have probably resulted from recrystallization of the borders of original rounded grains.

Most of the compact rounded grains fall into a size-class which is similar to the size-class of the associated heavy mineral components. Grains larger than 1 mm. across are exceptional, and only one individual larger than 2 mm. across was noted. This individual (see Plate 32) has been extensively replaced by pyrrhotite along two main directions, leaving angular island remnants of the original pyrite. This type of replacement of pyrite by pyrrhotite is fairly common, and all stages can be observed (see Plates 32 and 43). In some cases, in common with other heavy mineral components, extensive shattering may be conspicuous. The original, rounded grains may be effectively concealed by secondary, crystalline pyrite growths. Where the latter material is of the porous variety, the original grain is readily discernible (see Plate 33). Where the original, rounded grains are surrounded by compact, secondary, crystalline pyrite, however, the

original form may only become apparent after etching with acid. In many cases, the rounded grains are closely associated with undoubted heavy minerals (see Plate 34), and there is often a tendency for such individuals to be concentrated along footwall contacts. Well-preserved, rounded grains, which do not show signs of recrystallization, or which are not surrounded by secondary, crystalline material, are, when associated with minerals such as chlorite and chloritoid, invariably surrounded by the last-mentioned two minerals. Some of the individuals contain irregular specks of pyrrhotite and/or chalcopyrite, and it is thought that this material must have been introduced into the matrix within the particular rounded pyrite grain.

(2) Compact Rounded Pyrite Pseudomorphs

The most widely held view as to the origin of the rounded pyrite is that it has resulted from the pyritization of an original "black sand" constituent of the matrix. Rounded pyrite grains which could have resulted in this way are, however, extremely rare. If pyritization of hematite or magnetite had taken place, no relict structures would be expected, as these minerals are usually homogeneous in composition, and exhibit no unmixing characteristics. Incomplete replacement in some areas would, however, be possible, but no such grains were observed during the present investigation. A few grains of rounded pyrite containing parallel orientated slivers of rutile were observed, and it is probable that these individuals represent the pyritized product of original titan-magnetite grains. The pyrite formed from the magnetite portion, and the rutile from the titanium-bearing portion. Delicate rutile or leucoxenic skeletons, forming a type of Wiedmanstettan texture, have probably resulted from the titanium-rich exsolution portion of original titan-magnetite. In such cases, the magnetite portion has often disappeared (see Plate 3). The minute, irregular specks of chalcopyrite or pyrrhotite in some grains could possibly have resulted from the pyritization of some original "black sand" constituent.

Pyrite pseudomorphs after former banded ironstones and similar rocks are rare. Such replacement may, however, afford an explanation for some pyrite grains which have a banded appearance due to slightly bluish colouration of the mineral along certain zones. Etching with HNO_3 exaggerates these zones. No pseudomorphs of pyrite after limonite or similar material, as described by Ramdohr (1959) from the Black Reef, were observed.

(3) Pebble Pyrite Pseudomorphs

The replacement of small pebbles, especially of the fine-grained chert variety, is fairly common in some areas. The first stage appears to be the replacement of the chert along certain zones by small particles of pyrite. In the final stage, the whole pebble succumbs to replacement, and in such instances it may be difficult to distinguish this pseudomorph from an original pebble or granule of rounded pyrite. Pyrite in the latter form (i.e. as original pebbles or granules, as distinct from rounded grains) are thought to be rare, however.

(4) Loosely-Knit Skeletal Pyrite

Rounded grains of skeletal pyrite occur relatively abundantly in the reefs studied. Grains are often particularly noticeable in samples containing abundant compact rounded pyrite, and, where in contact with the latter variety, may show the effects of corrosion. Individual grains vary greatly in size and are almost invariably larger than adjacent compact rounded grains (see Plate 35).

Close examination reveals a loosely-knit structure with characteristic octohedral crosses (see Plate 36). It is quite obvious that this material could not have withstood the rigors of transportation, and it appears as though the nodules formed in situ from the

replacement or, more correctly, infiltration of pyrite into some pre-existing, rounded, loosely-constructed aggregate. The formation of the octahedral crosses, and the development of small flakes of pyrite within the porous portion of this material, which is usually granular, appear to be the first stage in the construction of a skeletal pyrite nodule. This is followed by the introduction of more and more pyrite into the porous nodule, until complete pyritization forms a compact mass, very similar in appearance to the compact, original, rounded pyrite grains, but usually larger. This process of pyritization usually takes place from the outer margin inwards, or, more rarely, transgresses from one side of a grain to the other. The nature of the original grain-type which gave rise to these individuals is obscure. It seems likely that the type of texture observed could have resulted from the replacement of loosely-packed chert or arkosic material, which came into the conglomerate as a clastic constituent. Close examination of Plate 36 reveals that the pyrite surrounds discrete grains giving rise to the octohedral crosses. Ramdohr (1959) considered the possibility of lumps of iron silicate gel, or mixed silica-limonite gel, as starting points for the formation of porous pyrite nodules.

In some cases, the porous nature of these individuals has enabled gold, pyrrhotite, and chalcopyrite to penetrate into available spaces before completion of pyritization (see Plate 37). Thus, some of the porous nodules contain large amounts of finely-disseminated gold which is not present in the more compact varieties of pyrite. The gold is seen coating discrete particles of pyrite within the nodule, and has apparently diffused inwards from the matrix. It is noteworthy that, where porous nodules contain gold, the adjacent matrix almost invariably contains gold in abundance. Various stages in the formation of these gold-rich pyrite nodules can be seen. It appears as though initial pyritization was followed closely by the infiltration of gold into suitable porous areas, coating the pyrite (see Plate 37). The introduction of gold was then followed by complete pyritization of the nodule, with the gold trapped inside having a characteristic arcuate shape. Chalcopyrite often behaves in a similar way, although it appears to be more mobile than the gold. Some of the gold and chalcopyrite occurring in apparently compact, rounded or irregular pyrite grains could possibly have originated in a similar manner. Extensive replacement of pyrite by pyrrhotite could be due to open-textured pyrite being more easily converted into pyrrhotite (Ramdohr, 1959).

(5) Compact Skeletal Pyrite

In a number of cases, complete replacement of porous nodules by pyrite has given rise to compact rounded grains. These grains are usually recognized by their large size and abundant inclusions, but can be similar to the original, rounded, compact pyrite grains.

(ii) Secondary Pyrite

This type of pyrite is of major importance in some parts of the reefs studied, and may occur to the exclusion of rounded pyrite. In most cases, it has probably been derived almost exclusively from the reconstitution or remobilization of original, rounded grains.

(1) Compact Crystalline Pyrite

Compact, crystalline pyrite is widely distributed in the reefs studied. Small, irregular grains and well-formed crystals are often scattered throughout footwall material, more especially in the shale footwalls of the Black Bar and Jeppestown shale.

Most of the compact crystalline pyrite examined is of the isotropic variety, but definite anisotropic pyrite has been observed. In places, this anisotropic crystalline pyrite

may constitute about half the pyrite present in a particular section. Stanton (1957) has shown that pyrite is generally anisotropic to varying degrees, and has ascribed this to polishing phenomena. In the cases under consideration, however, it seems likely that the anisotropism may be due to a slightly different phase of the mineral. In normal light, the pyrite is seen to be of a very faint, blotchy, light brass yellow to blue colour. This pyrite tarnishes easily, and is often associated with chalcopyrite-rich areas of the matrix.

The size of the crystalline pyrite is very variable, ranging from minute crystals to very large crystals and irregular masses. In most cases, it is recognized as well-formed crystals (see Plate 2) and irregular grains which, in a number of instances, represent outgrowths on original rounded grains. In many instances, the original grain outline cannot be recognized, but, in some individuals, it may be demarcated by the growth of delicate crystals (see Plate 38).

When pyrite does occur in pyrrhotite-rich samples, it is usually of the compact crystalline variety, although porous crystals have been observed. In such cases, the pyrite is confined almost entirely to the pebbles which appear to have afforded a protection against pyrrhotization. Even in such instances, the pyrite may be rimmed by pyrrhotite. Gold is commonly associated with the irregular crystalline variety, and is found at the edges of irregular compact grains (see Plate 39).

(2) Porous Crystalline Pyrite

Porous crystalline pyrite is not as common as the compact variety, but in some cases occurs abundantly in very striking forms. It may, at times, constitute up to 50% of the total pyrite present in a particular sample. It is often closely associated with the compact crystalline material, and grades into the latter variety.

The size of crystals is variable, but they are usually fairly large. In most cases, the porous crystals surround original, compact, rounded grains, and the original, rounded outlines of the latter are often clearly discernible (see Plate 33). In a few cases, large masses of beautifully zoned pyrite occur with the compact crystalline variety, but do not surround original, rounded grains (see Plate 40). Close examination reveals that the zones are defined by aligned strings of pores (see Plate 41). This zonal type of pyrite indicates, according to Ramdohr (1959), growth of pyrite *in situ*. It is clear that the zones are parallel to the outlines of the crystals, although such outlines may be obliterated by corrosion. It seems unlikely that such loosely-constructed material could have withstood the rigors of transportation, and it is concluded that the crystals grew by accretion *in situ*. According to Ramdohr (1959), this type of pyrite is younger than the compact crystalline variety, and grew fairly quickly at lower temperature.

Besides its frequent occurrence around nuclei of rounded pyrite, the growth of porous crystalline pyrite around such minerals as zircon, chromite, and uraninite clearly demonstrates its secondary nature. Well-developed porous crystalline pyrite is sometimes conspicuous near dykes. Here, individual grains are usually much smaller than those described above, and tend to be more porous in the middle of the crystal, with more compact pyrite forming the margin. Some crystals may contain small ragged flakes of pyrrhotite.

(3) Vein Pyrite

This variety of pyrite appears to be the last to have formed, and is probably related to the compact crystalline material. It is of an extremely mobile nature, as demonstrated by its occurrence in very small veinlets. These veins are sometimes only .002 mm. in width, and are frequently found cutting fractured earlier minerals, such as zircon.

(iii) Origin and Paragenesis of Pyrite

It is considered likely that the majority of rounded pyrite grains entered the conglomerate in the form of detrital particles which owe their shape to processes of sedimentary transport and reworking. In some instances, it is probable that rounded grains (those containing aligned inclusions of rutile) have been derived from titan-magnetite, but, in the majority of cases, there is no reason to believe, and, in fact, it seems improbable, that the rounded pyrite resulted from the replacement of what have been termed "black sand" constituents. Whereas it is true that heavy mineral constituents such as magnetite and hematite (which do not exhibit unmixing characteristics), on being replaced to form pyrite, would exhibit no relict structures, at least some signs of the incomplete replacement of these minerals by the sulphide-bearing solutions or gasses could be expected. Neither hematite or magnetite was observed with certainty in the samples studied, and this is in accord with the observations of Liebenberg (1955), Ramdohr (1959), and others. It seems improbable that such perfect pyritization of iron-bearing; rounded, detrital minerals could have taken place over approximately 80 strike-miles of reef studied. The passage of sulphur-bearing gasses or solutions over such large areas, without any signs of interconnecting veinlets, seems improbable. Complete absence of oxidizing effects on the surface of rounded pyrite grains indicates that deposition must have taken place in an environment relatively free of oxygen. If the pyrite is a placer mineral, as is thought, it is likely that the mineral grains were surrounded, for the most part, by water, either in the rivers which delivered them to the depositional basin, or in the depository under fluvial, deltaic, or marine conditions. It has been shown (Lindgren, 1933) that oxidation of a mineral such as pyrite, which oxidizes very readily, is retarded when covered by water.

For the sake of simplicity, the detrital grains of pyrite are referred to as the primary generation of pyrite (see Figure 2). Besides this type of pyrite, there exists an abundance of material which, in its present form, has not undergone attrition under sedimentary conditions. This second generation of pyrite is present as crystalline crusts and irregular grains. Indications are that this generation has been derived from the reconstitution and remobilization of original pyrite under conditions of metamorphism. The alternative sources of this material are hydrothermal solutions associated with igneous bodies intrusive into Witwatersrand rocks. It is true that, in certain places, intrusive dykes have influenced the secondary sulphide content of the reef to varying degrees, but this effect is very local, and does not account for the bulk of the second generation of pyrite. The secondary pyrite often migrates to the more porous areas of the matrix, and concentrates in zones amenable to replacement or infiltration. Chert pebbles are particularly susceptible to such replacement. Infiltration of pyrite into porous nodules in the matrix is fairly common, and is sometimes accompanied by gold of a slightly younger age, where the latter mineral is abundant in the adjoining matrix. Most of the remobilization of gold and such sulphides as pyrrhotite, chalcopyrite, and skutterudite, appears to have taken place after the main phase of secondary pyrite formation.

It is probable that a very late (third) generation of pyrite is responsible for cementing gold in porous, second-generation pyrite nodules, and for minute veinlets which are seen cutting most constituents in the matrix. This generation of pyrite occurs on a very limited scale (see Figure 2).

In postulating an original detrital origin for most of the pyrite present in the reefs studied, including most of the second-generation pyrite, it is necessary to enquire into the origin of the mineral. What was the source of the vast amount of pyrite in the reefs studied, and in the rocks of the Witwatersrand System as a whole? It is well known that most magmatic gold deposits contain associated sulphides, of which pyrite is usually the most common. Little material now exists to give a clue to the nature of the mineralized veins or lodes which contributed gold to the Witwatersrand Basin. Swaziland System rocks of the Barberton area, however, contain vein and lode deposits of gold, similar to

those which may have contributed gold to the Witwatersrand depositary. By far the most abundant sulphide associated with these deposits is pyrite. The liberation of gold from similar sources must have resulted in the liberation of large amounts of pyrite which, it is believed, was deposited with the gold under sedimentary conditions.

(b) Pyrrhotite

This mineral occurs erratically in the three reefs studied. Its development in the Main Reef is very limited (except at E.R.P.M.), whereas it may be a very important mineral in the Main Reef Leader (East Rand). Its distribution in the latter conglomerate is extremely erratic where, over a few feet of reef, it may vary from 90% of the total ore minerals to less than 10%. No pyrrhotite was noted in any of the footwall horizons examined.

The mineral is fairly brittle, especially where it has been subjected to slight oxidation, and this usually results in a poor polish, with pitted surfaces. The strong anisotropic nature is a very distinctive feature, and in some cases the inhomogeneous character of the mineral is shown by pinkish-brown, flame-like lamellae which were recognized by Ramdohr (1959). Of more common occurrence are the flame-like lamellae of pentlandite (see Plate 42), normally limited to high-temperature nickeliferous pyrrhotite. The mineral almost invariably occurs in the form of irregular masses of varying size. Pyrrhotite displaying crystal outlines within the matrix was not observed, and individuals showing crystal outlines were seen only in pebbles, where they probably represent pseudomorphous replacement of some pre-existing constituent. These crystals are usually prismatic, the most common forms being rods and blades. In a number of cases, pyrrhotite occurs to the complete exclusion of pyrite, and, in such instances, forms irregular masses which may, or may not, contain pentlandite lamellae. When associated with uraninite, small flakes are the characteristic form.

Pyrrhotite is commonly associated with pyrite, and in the Main Reef Leader (East Rand) may take the place of pyrite entirely. In the majority of samples studied, various stages in the process of replacement of pyrite by pyrrhotite were seen. Elongated stringers of pyrite (of the crystalline variety), left behind as remnants in the enclosing pyrrhotite, are most common. In other cases, in rounded pyrite, preferential replacement of pyrite takes place along two controlling directions, at right angles to each other. All stages of this type of replacement can be seen (see Plates 32 and 43). In general, rounded pyrite grains are not directly associated with large masses of irregular pyrrhotite, although examples of pyrrhotite surrounding rounded pyrite, but not replacing it, are sometimes met with (see Plate 44). In a few instances, grains of rounded pyrite contain small flakes of pyrrhotite, and it seems likely, as proposed by Ramdohr (1959), that this pyrrhotite is unrelated to that described above, and that it has made its way into the basket as an inclusion in a rounded pyrite grain, derived from an external source.

Pyrrhotite is often, but not invariably, associated with pentlandite. Flame-like lamellae of this mineral occur in a relatively large percentage of the pyrrhotite examined. The lamellae have a definite crystallographic control, and are aligned parallel to 0001 (Ramdohr, 1959) (see Plate 42). They are particularly well-developed in the small amounts of pyrrhotite occurring within the Pebbleless Bastard, a reef closely associated with the Main Reef at the Rose Deep Mine. In one sample, the pyrrhotite appears to have been twinned, and the two sets of pentlandite lamellae occurring on either side of the twin plane are aligned at about right angles to each other, on opposite sides of the twin plane, giving a type of herring-bone texture (see Plate 45). This type of relationship suggests that the pentlandite is an exsolution product of the pyrrhotite, and that it is of the variety which is normally found in very high-temperature nickeliferous pyrrhotite (Ramdohr, 1959). It seems likely, therefore, that the formation of pentlandite was controlled to a certain extent by temperature.

The close association of pyrrhotite with chalcopyrite is apparent in many samples where the pyrrhotite is usually the dominant mineral. Age relationships between the two minerals are not clear, but the chalcopyrite appears to be the younger of the two, in most cases. It is possible that the chalcopyrite is an exsolution product of the pyrrhotite.

In most instances, there seems to be no obvious relationship between pyrrhotite and gold. In a number of samples with pyrrhotite as the dominant ore mineral, gold is no more plentiful than in an average sample where the dominant ore mineral is pyrite. Gold particles surrounded by pyrrhotite usually have regular outlines, and differ from the hackly grains of gold occurring within the matrix. Pelletier (1940), however, concluded that pyrrhotite acts as an enriching factor in the ore. This conclusion is supported, to some extent, by the fact that in the samples studied, the variety of pyrrhotite which characteristically surrounds grains of uraninite is often closely associated with gold (see Plate 46).

One of the more important modes of occurrence of pyrrhotite, but by no means the most common, besides the more usual forms of occurrence described above, is with thucholite and, more especially, uraninite. This association was noted frequently, and appears to be of some significance. In many samples, especially from the Main Reef, the only pyrrhotite visible is that occurring in close association with the small amount of uraninite which may be present. This type of pyrrhotite has a different form and mode of formation to that described above. The mineral is commonly seen filling fractures in the primary uraninite (see Plate 46), in the form of thin films or veins. This type of pyrrhotite is closely associated with what appears to be uraninite of secondary origin, as well as with gold (see Plate 46). Some of the pyrrhotite occurs with small amounts of galena, presumably produced radiogenetically. In some cases, primary uraninite grains are almost entirely engulfed by pyrrhotite which may contain small amounts of pentlandite. In other instances, small scattered flakes of pyrrhotite closely associated with uraninite grains are the only sign of the mineral. In a similar way, abundant small flakes of the mineral are frequently associated with grains of leucoxene.

Besides the crystal pseudomorphs described above, large masses of pyrrhotite are sometimes found filling fractures within quartz pebbles. This material, which is frequently associated with chalcopyrite, has been introduced by infiltration.

In this present form, the mineral is obviously not detrital, although original rounded detrital grains may, in places, have been remobilized. It is thought that most of the pyrrhotite examined has been derived from the dissociation of pyrite of suitable composition, usually proceeding along definite zones which were probably more susceptible to pyrrhotitization (see Plates 32 and 43). Dynamic, more than thermal, metamorphism is thought to have been responsible for the formation of the mineral from pyrite. In most cases, this took place at a very late stage in the paragenetic sequence, i.e. at about the same time as the redistribution of the gold and the rare sulphides. Some of the pyrrhotite was formed as a result of the metamorphic effect of intrusive dykes, but numerous observations by many investigators have shown that this is always on a local scale and within a distance which rarely exceeds 100 feet from the intrusive body. The occurrence of exsolution lamellae of pentlandite is, according to Ramdohr (1959), limited to very high-temperature nickeliferous pyrrhotite, the nickel being contained in minute inclusions of millerite within the original pyrite.

In some cases, especially in the Main Reef Leader (East Rand), the development of pyrrhotite and an increase in gold values are conspicuous along footwall contacts. A good example of this is to be found in the Main Reef Leader (East Rand) in the Modderfontein East Mine at No. 1 Shaft, 5 C/22 Stope, North Face, 70 feet below 21-Level. In this area, the channel width is 38 inches, with a reef width of 30 inches. Seven samples of reef were taken over 10 feet, five from the footwall contact (the footwall in this area being Jeppestown shale) and two from near the hangingwall quartzite

contact (see Figure 3a). In the five samples from the footwall contact, the pyrrhotite content averaged over 90%, with the highest pyrite content being less than 4%. The gold tenor was high. On the other hand, the two samples taken near the hangingwall contact contained over 88% pyrite (mainly of the compact rounded type), with the highest pyrrhotite content being just over 1%. The gold tenor was distinctly lower. The rock in the immediate vicinity of the footwall has undergone severe shearing stress. The footwall shale is crowded with crenulation folds (see Plate 16), and some of the reef pebbles lying on the contact have been severely deformed. In addition, the reef contains abundant evidence of pressure shadows (now filled mainly with quartz), and many of the sulphides have been stretched parallel to the general schistosity (see Plate 19). It is contended that the development of pyrrhotite in the lower portion of the reef is largely due to this stress, and that the higher-than-normal gold values are a manifestation either of an originally higher gold content at the base of the reef, or of redistribution of gold at the time of the formation of the pyrrhotite. It is thought likely that the intense shearing along the footwall contact resulted in the fracturing of pyrite and other hard detrital minerals. This fracturing of the pyrite produced an open texture, not present in the pyrite grains higher up in the reef. According to Ramdohr (1959), any open-textured pyrite would react much more readily than the compact masses, and would more readily be changed into pyrrhotite.

The influence of dykes in producing pyrrhotite in reef horizons was well demonstrated in five random samples of Main Reef Leader (East Rand) from Vlakfontein, J.V. Shaft, 8 Inter, W.20 Winze. The reef in this area is situated on the flank of an anticline, in a section where dykes and sills of the quartz-dolerite type occur, the distance to the nearest intrusive being approximately 50 feet. Pyrite is almost entirely lacking, and in all cases pyrrhotite constitutes well over 95% of the total ore minerals present. Lack of stress phenomena in the reef and footwall, the paucity of pyrite, and the proximity of the sampling locality to the intrusives leads to the conclusion that, in this case, the presence of pyrrhotite in the reef is due to the influence of magmatic intrusions.

Another type of pyrrhotite, apparently having no connection with dissociation of pyrite, influence of stress fields, or proximity to intrusives, is that which occurs closely associated with uraninite. This association has been noted by Ramdohr (1959) and Liebenberg (1955). In many cases, this pyrrhotite constitutes the only form of the mineral occurring in a particular sample, and could not have migrated from some nearby mass of pyrrhotite. It is invariably younger in age than the uraninite, and small veinlets are seen penetrating the latter mineral. It is thought that the uraninite is responsible for the formation of this pyrrhotite, possibly by some obscure process, such as radioactive heating.

Most of the pyrrhotite is clearly related to the third phase of mineralization, associated with the main period of remobilization of gold (see Figure 2).

(c) Thucholite

Thucholite is generally of fairly minor importance, and its almost complete exclusion from the Main Reef is conspicuous. The mineral is relatively abundant in the Main Reef Leader of the Central and East Rand, and most samples studied contain a number of grains. The distribution of the hydrocarbon is, however, erratic. In some cases it is the dominant mineral, and may constitute up to 90% of the total volume of ore minerals. No thucholite was noted in any of the footwall horizons examined, although concentrations of carbon pillules along footwall contacts are fairly common.

Davidson and Bowie (1951) concluded that the "carbon", referred to in earlier publications, was in the form of a radioactive hydrocarbon which was found to replace

original uraninite grains in various degrees. This radioactive hydrocarbon is of the thucholite-type, and the word thucholite is now synonymous with the term "carbon". The thucholite examined in the present investigation is generally strongly anisotropic, and has a blotchy appearance under polarized light. According to Liebenberg (1955), the above properties are indicative of the more radioactive variety of thucholite, i.e. material with a fairly high uranium content. In the samples studied, the thucholite occurs typically in the form of black, opaque, nodular grains, with a dull, wart-like exterior and vitreous to adamantine lustre on fractured surfaces. The diameters of these grains, although rarely exceeding 1 mm., are generally larger than the diameters of the heavy minerals. Grain edges are usually irregular, giving a type of serrated appearance in section. Where in contact with original matrix constituents, such as chromite or zircon, the thucholite invariably tends to engulf the latter minerals. In samples rich in thucholite, the spherical grains tend to merge to form compact masses which have the appearance of anthracite. In some cases, the identity of the original spherical grains is lost. Columnar thucholite, as described by Liebenberg (1955), was not observed, probably because of the general paucity of the hydrocarbon in the reefs studied.

Most thucholite grains, on close inspection, are seen to contain angular fragments of uraninite of various sizes (see Plates 47 and 48). The uranium content of the thucholite is explained by the fact that inclusions of uraninite are nearly always present, and often appear to be remnants of larger grains which have been replaced by the hydrocarbon. It seems likely that original, probably fractured, grains of uraninite were replaced along fractures by the thucholite, and in some cases completely assimilated. It is doubtful, however, whether the size of the thucholite nodules reflects the size of the original uraninite grain. In many cases, the uraninite has completely disappeared. Relationships seem to suggest that the secondary uraninite is younger in age than the hydrocarbon.

Samples rich in gold often contain an unusual amount of thucholite, and Horwood (1910) suggested that this carbonaceous matter might have acted as a precipitating agent for the gold. The gold occurs in a number of ways, most commonly as thick coatings on thucholite grains, and more rarely as disseminated specks within thucholite nodules (see Plate 48). Where the gold occurs in the latter manner, it is almost invariably restricted to the uraninite inclusions within the thucholite. In most cases, the gold appears to be younger than the hydrocarbon.

The origin of the thucholite in the Witwatersrand banket has been discussed at length by Liebenberg (1955), and, as its occurrence is fairly limited in the reefs studied, only brief mention will be made of it. The hydrocarbon is invariably seen replacing uraninite grains, to a greater or lesser degree, and this accounts for the radioactive nature of the substance (Liebenberg, 1955). In the samples studied, the process of replacement of uraninite by hydrocarbon is usually almost complete, and only small fragments of the uraninite are left behind. In view of its erratic occurrence and the fact that most of the uraninite is free of hydrocarbon, it seems unlikely that the original material that subsequently gave rise to the thucholite could have been detrital in the sense that the uraninite, gold, zircon, and chromite were. It is possible that the original source of the hydrocarbon was some sort of primitive organic life which thrived in certain environments associated with particular reef horizons or particular parts of one reef. The possibility also exists that the uraninite acted as a precipitating agent for the hydrocarbon which, as has been contended by Liebenberg (1955) and others, was originally in the form of a gas. Hydrocarbon gas in the form of methane is present in many Witwatersrand mines today. According to Liebenberg (1955), irradiation of this gaseous hydrocarbon, which was possibly derived from primitive organic life, by detrital uraninite was a prerequisite for the formation of thucholite. It appears that a certain variety of hydrocarbonaceous material can be polymerized by radioactive emanations, whereby solid hydrocarbons are precipitated.

Mineralogical observations indicate that the main phase of thucholite formation took place at a fairly early stage in the mineral paragenesis, probably partly contemporaneously with the second generation of pyrite, but prior to the redeposition of the main mass of gold and secondary sulphides.

(d) Chalcopyrite

Chalcopyrite usually occurs in insignificant amounts, but may constitute a fair proportion of the sulphides in certain cases. In some samples, apparently of isolated occurrence, it may be the dominant sulphide. As in the case of pyrrhotite, it is often restricted to pebbles within a particular sample. The mineral is almost entirely exclusive to the reef horizons, and only a few isolated, irregular patches were noted in footwall or hangingwall horizons.

The chalcopyrite occurring in the reefs studied generally appears to be very homogeneous in composition. No exsolution products, such as sphalerite, vallerite, or cubanite were observed, although sphalerite is sometimes closely associated with chalcopyrite and pyrrhotite. The mineral is yellowish-green in colour, with no marked anisotropism. In a number of cases, applying particularly to larger grains, very well-developed polysynthetic twinning was observed. The mineral exhibits no definite age relationships with other minerals, and occurs in characteristic irregular xenomorphic masses or grains within the matrix. The size of the chalcopyrite masses varies greatly from individuals up to a few mm. across, which are easily seen in hand specimens, to minute flakes which are usually associated with uraninite.

The most striking characteristic of the chalcopyrite is its almost constant, although not invariable, association with pyrrhotite. It usually exhibits mutual boundary relationships with the latter mineral, but replacement textures have been observed. Pelletier (1940) noted the association of the two minerals in the basket as a whole, and stated that "the relative abundance of chalcopyrite is largely a function of that of the pyrrhotite". The chalcopyrite usually occurs to a much lesser extent than the pyrrhotite, where this association is present. The very mobile nature of the mineral is often apparent, and is demonstrated where chalcopyrite is seen to diffuse into fractured pebbles to a greater depth than the pyrrhotite. The mineral is often associated with pyrite, especially of the porous variety, where it penetrates, sometimes together with gold, the porous structure. In a similar way, oval masses, presumably of a siliceous nature, occurring within the matrix, are often riddled with irregular flakes and veinlets of chalcopyrite. This material has been derived by infiltration into a porous substance, as in the case of the porous pyrite nodules. Abundant minute veins, predominantly of chalcopyrite, but containing, in addition, small specks of pyrrhotite, are often seen anastomosing through fractured grains of compact pyrite. As in the case of the pyrrhotite, irregular grains of chalcopyrite are frequently observed in pyrite grains of both the crystalline and rounded varieties.

Moulding of chalcopyrite on, and within, bunches and rosettes of chloritoid crystals or other phyllosilicates is common, and in some cases the mineral may even penetrate along cleavage traces.

In some areas, just as in the case of pyrrhotite, chalcopyrite is closely associated with grains of thucholite, and more especially uraninite. In most instances, it surrounds the uraninite, and frequently forms veinlets which cut through both thucholite and uraninite grains. As in the case of pyrrhotite, the mineral is restricted to uraninite inclusions, where the latter mineral is partially replaced by thucholite.

Irregular masses of chalcopyrite are sometimes found in vein quartz pebbles where the surrounding matrix is devoid of the mineral. It is probable that some of this chalcopyrite was brought into the conglomerate within the enclosing pebble.

Chalcopyrite, together with many of the other less abundant sulphides, was one of the last minerals to crystallize, and is more-or-less contemporaneous with the phase of redeposition of the gold. It is doubtful whether any of the chalcopyrite entered the conglomerate in the form of detrital grains. The very erratic distribution of the mineral points to its being a reconstituted mineral, and its close association with pyrrhotite is possibly indicative of exsolution. In some cases, however, large amounts of chalcopyrite may occur with little or no pyrrhotite. A good example of this is afforded by a set of seven samples from the Main Reef Leader (East Rand) at the Modderfontein East Mine, No. 2 Shaft, 11^A/11 Stop, North Mid., 350 feet above 11-Level. In this part of the mine, where the sulphide and carbon mineralization is slightly higher than normal, the hangingwall is composed of quartzite and the footwall of shale. The sampling localities are depicted graphically in Figure 3b, where it can be seen that five samples, k4710 to k4714, have been taken from the footwall contact, and two samples, k4708 and k4709, from a quartzite parting in the reef. All the samples taken from the footwall contact contain a relatively large percentage of chalcopyrite (up to 46.42% in the case of Sample k4713). The general absence of pyrrhotite indicates that the mineral is not always a close associate of chalcopyrite. The high carbon content is noteworthy, and it is not known whether the association with chalcopyrite in this case is fortuitous or not. The explanation of these observations is difficult. As there is no evidence of a basic intrusion for the supply of the chalcopyrite and carbon, as well as of the abnormally high gold content, it is thought that these minerals resulted from the reconstitution or remobilization of detrital minerals on the footwall contact. The abundance of carbon might be a manifestation of the presence of numerous uraninite grains which were concentrated along the footwall contact prior to the commencement of the process of thucholitization. Samples k4708 and k4709 (see Figure 3b) are included to show the complete lack of sulphides or gold in quartzitic partings in the reef.

(e) Arsenopyrite

Arsenopyrite is a very constant component of the reefs studied, and normally constitutes about 3% of the ore minerals, but in places this figure may be as high as 5% and more. In such instances, up to 50 grains can be counted in one standard-size polished section. It occurs most abundantly in the Main Reef Leader (East Rand) and the Main Reef of the West Wits Line. No arsenopyrite was noted in any of the footwall or hangingwall beds examined.

The composition of the arsenopyrite appears to be very variable, and in only a few sections, such as at Modder East, do true arsenopyrite grains, identified by their characteristic strong anisotropism and white colour, predominate. No grains exhibiting the mimetic twin lamellae of the monoclinic variety, danaite, were noted. A fair number of grains appear to belong to the variety glaucodot, which has rhombic symmetry and a cobalt content which exceeds 10%. These grains are identified by their weak anisotropism and slight pinkish tint, not characteristic of arsenopyrite. Individual grains occur almost exclusively as rounded, fairly spherical individuals, generally slightly smaller than the leucoxene and pyrite fractions. Plate 49 shows a typical well-rounded arsenopyrite grain, surrounded by pyrrhotite. Crystalline arsenopyrite, in the form of secondary overgrowths on original rounded grains, is rare, but has been observed. Very well-developed rhombohedra of arsenopyrite are sometimes encountered in quartz pebbles, but it is almost certain that these individuals have been brought into the conglomerate within the pebbles (see Plate 50). The edges of such crystals show no signs of abrasion whatsoever. Fractured grains of arsenopyrite are fairly common, giving a type of "exploded bomb" texture.

Rounded grains of arsenopyrite are most commonly found in close association with rounded pyrite grains and other heavy minerals. In places, there may be marked

concentrations of the mineral along footwall contacts. Of interest is the fact that in one area of the Modder East Mine, the reef, containing rounded arsenopyrite and rounded pyrite grains, grades into reef which contains rounded arsenopyrite grains and roughly spherical masses of pyrrhotite over a distance of a few feet. In other areas, it has been noted that arsenopyrite is usually very conspicuous in samples containing abundant pyrrhotite, and well-rounded grains are often imbedded in the pyrrhotite (see Plate 49). This association demonstrates the age relationship of these two minerals, and lends support to the contention that the arsenopyrite is of detrital origin. In view of the fact that rounded grains of arsenopyrite are almost invariably associated with rounded grains of pyrite and other heavy mineral constituents, it is suggested that the association of large amounts of pyrrhotite with numerous grains of rounded arsenopyrite is a manifestation of the fact that the rounded pyrite, which was originally present, has been converted into pyrrhotite. In places where the arsenopyrite has been fractured, minute veinlets of pyrrhotite are sometimes seen filling the fractures, and in some instances the pyrrhotite has almost completely engulfed the arsenopyrite, leaving behind small remnants of the latter mineral. In such cases, on close inspection, the original outline of the arsenopyrite can roughly be delineated.

Arsenopyrite is rarely found within pebbles, but, as mentioned above, occasional well-formed rhombohedral crystals are sometimes met with. No veinlets of arsenopyrite penetrating pebbles were observed.

Most of the arsenopyrite examined belongs to the primary phase of mineralization, i.e. it was brought into the conglomerate in the form of rounded grains. Crystalline overgrowths on original grains, although rare, have been observed, and belong to the second phase of mineralization. The above also applies to the rounded grains of glaucodot and cobaltite encountered. In seeking a source for the rounded arsenopyrite grains, no serious problem is presented. The mineral is a common associate of gold-sulphide veins, and is frequently found in the hydrothermal gold veins of the Barberton area.

(f) Uraninite

Uraninite grains are not generally conspicuous in the reefs studied, and are entirely absent from a number of sections. The mineral occurs most commonly in the Main Reef Leader (East Rand), but is very limited in its occurrence in the Main Reef. It is often found in abundance with pyrite, leucoxene, zircon, and chromite grains along footwall contacts or features such as false footwalls within the reef. No uraninite was observed in any of the footwall or hangingwall horizons examined, and the mineral seems to be confined in its occurrence to reef horizons.

The occurrence of uraninite in mineral concentrates was first noted by Cooper (1923), but it was only after nearly two decades had elapsed that the vast resources and value of the Witwatersrand Basin as a uranium producer were realised. It has proved to be one of the most controversial minerals of the basin, and many arguments have been put forward, each advocating entirely different origins. Davidson and Bowie (1951) contended that the uraninite is of the hydrothermal, colloidal pitchblende-type, but Liebenberg (1955) and Ramdohr (1959) found no evidence supporting this contention. Both these investigators favour the idea that the uraninite is of placer origin, and of the crystalline variety.

Most of the uraninite grains are grey in colour, with a fairly rough pitted surface which may contain specks of galena. All the grains are isotropic. Uraninite, other than that which is included in the thucholite in the form of angular fragments, occurs relatively widely, if not abundantly, in the reefs studied. Individual grains are commonly

rounded, and spherical to oval in shape, generally showing definite signs of abrasion (see Plate 51). Some grains, however, exhibit the remnants of crystal outlines, indicating that in certain cases, at least, transport was not over very great distances. Grains generally tend to occur as randomly scattered individuals, although aggregates of up to five, or even ten, grains have been observed. The exact outline of the grains is, in some instances, concealed by a hazy substance, composed usually of small specks of radiogenic galena, flakes of pyrrhotite or chalcopyrite, and leucoxenic material. In such cases, the original shape can often only be seen in polarized light, when it is defined as a dark sphere. These grains, which are fairly common in some areas of the reefs examined, are similar to the altered individuals referred to as uraninite ghosts by Ramdohr (1959). Fissuring, which is a common characteristic of radioactive minerals, is generally a conspicuous feature of the uraninite grains studied. Many individuals appear to have been shattered cataastically, probably at about the time of reef deposition. These grains have almost invariably been cemented by remobilized material which includes gold and pyrrhotite (see Plate 52). Most of the uraninite grains are distinctly smaller than associated heavy minerals.

Secondary uraninite, as described by Liebenberg (1955), is generally not conspicuous in the reefs studied. It occurs most frequently as a cementing material in areas of reef where aggregates of uraninite grains are plentiful. This material, which has probably resulted from the reconstitution of primary grains, is slightly darker, and contains fewer galena inclusions than the original material. It is often closely associated with pyrrhotite or chalcopyrite and sometimes gold.

The close association of uraninite with thucholite was noted in all sections which contained both minerals. The uraninite, as has been mentioned, occurs in the thucholite in the form of angular fragments (see Plates 47 and 48). The number and size of these fragments within a particular nodule of carbon vary. It seems likely that in most cases the uraninite fragments represent portions of originally fractured grains which have subsequently been replaced along fractures by the hydrocarbon.

Uraninite grains are often intimately associated with gold. In most cases, the gold is distinctly younger, and cross-cutting relationships are frequently encountered. Where grains have been fractured, cross-cutting veins of gold, often closely associated with pyrrhotite, may be seen (see Plate 52), but small specks or flakes of gold within, or surrounding, uraninite grains are more frequently met with (see Plate 51). The uraninite definitely appears to have an attraction for remobilized gold. Where uraninite particles occur within thucholite masses, gold, if present, is almost invariably restricted to the uraninite (see Plate 48).

The close association of much of the uraninite with small flakes and films of pyrrhotite (and more rarely chalcopyrite) is sometimes conspicuous. In the Main Reef, for example, the only pyrrhotite occurring within a particular sample occurs in the form of small flakes and films associated with isolated grains of uraninite. In other cases, aggregates of uraninite grains are almost completely surrounded by pyrrhotite (see Plate 46) which may, in addition, contain specks or blobs of galena, as well as gold. It therefore seems likely that the presence of uraninite plays a part in the formation or distribution of some of the pyrrhotite.

Galena is almost invariably associated with uraninite, usually in the form of tiny white specks, thin veins, or a mere dusting. According to Ramdohr (1959), the original material was lead of radiogenic origin, which has subsequently been reconstituted, by long association with sulphur, to form galena. In some cases, especially where primary and secondary uraninite are abundant, large masses of galena occur adjacent to the radioactive material. It is likely that this material is of radiogenic origin, and has migrated from the uraninite grains. No uraninite, either of primary or secondary origin, was noted in any pebbles examined.

The subject of uraninite in the Witwatersrand blanket has been exhaustively dealt with by Liebenberg (1955), and, as the mineral is not of economic importance in the reefs studied, only the most pertinent points concerning its origin, which have arisen out of the present study, will be discussed.

The majority of grains examined during the course of the investigation display rounded to sub-angular edges, and have a spherical to slightly oval form. The mineral is regarded as belonging to the primary phase of mineralization, i.e. it is considered to be a detrital mineral component. Uraninite grains are often concentrated along footwall contacts or false bedding planes within the reef, and are often associated with minerals of undoubted placer origin, such as zircon and chromite. The occurrence of the mineral is, however, more patchy than the other constituents, but this is probably due to its high specific gravity and small size. The narrow size range in which the uraninite grains occur (i.e. the good sorting of the grains), together with the size of individual particles, always smaller than associated heavy minerals, are two of the most important criteria in favour of a placer origin. In addition, age measurements on Witwatersrand uraninite have shown that the uraninite was formed prior to the commencement of deposition of the Witwatersrand sediments (Burger, Nicolaysen, and de Villiers, 1962; de Villiers, Burger and Nicolaysen, 1958; Louw, 1954). Davidson (1953) came to the conclusion that uraninite could not survive as a placer mineral, because of its unstable nature, and cited as evidence the almost complete lack of detrital uraninite in modern placers. More recently, Koen (1958) has demonstrated, by means of tests in an attrition cell, that Witwatersrand uraninite is capable of resisting mechanical wear, at least as successfully as monazite, and that the original material must have been stable. It has also been deduced that rounding in water of particles smaller than .75 mm. must be a very slow process, and it is clear that the size of the uraninite grains in the blanket ensured their physical stability. In addition, Zeschke (1960) found that detrital grains of uraninite occur continuously over a distance of one hundred miles in the river sand of the Indus river in Pakistan. Investigations concerning the hydraulic equilibrium of uraninite and two other constituents of undisputed detrital origin, chromite and zircon, were carried out by Koen (1961). It was found that these three minerals are in hydraulic equilibrium, and, on the assumption that the chromite and zircon are of undisputed detrital origin, it was argued that the uraninite is of detrital origin.

In their present form, many of the uraninite grains show signs of alteration, and, in places, secondary uraninite has developed, probably partly as a result of the replacement of original grains by hydrocarbon. In most cases, this secondary material, which is of minor importance in the reefs studied, is more or less contemporaneous with the main phase of redistribution of the gold and minor sulphides.

(g) Cobaltite

Rounded, usually spherical grains of cobaltite were noted infrequently in all the reefs studied. The edges of some grains have undergone little or no rounding, in which case the cubic nature of the mineral is apparent. Besides the rounded grains, there is a second variety which, in its present form, is of undoubted secondary origin. This type of cobaltite was noted only in the Main Reef Leader (East Rand) where it was seen surrounding primary constituents. No primary or secondary cobaltite was noted in any of the footwall or hangingwall horizons examined.

The irregular form of cobaltite appears to be of the secondary variety, which is distinguished from other white sulphides by its pinkish hue. Small, rounded, detrital grains of the mineral may be confused with arsenopyrite and glaucodot, and, for this reason, these three minerals were grouped together for size measurements. In most cases, the cobaltite was identified by its pinkish colour and lack of marked anisotropism. Primary grains of cobaltite occur in the form of well-rounded spherical to oval individuals, which tend to be slightly smaller than the associated heavy minerals. Some of the

irregular masses of secondary cobaltite may contain crystal faces, and there seems to be little doubt as to the epigenetic origin of the mineral in such cases. Cubes or pyritohedra of cobaltite have been observed in pebbles and in the matrix. It is probable that the individuals within the pebbles reached their present position within the protective coating of the pebble.

In some places, the occurrence of rounded cobaltite grains on footwall contacts, together with other rounded constituents, is distinctive. These grains may contain small inclusions of chalcopyrite and pyrrhotite. In samples rich in gold, irregular masses of cobaltite may be riddled with the metal (see Plate 53). It is possible that this gold has infiltrated into a porous nodule or mass of cobaltite in much the same way as the gold in the porous pyrite nodules. If this is the case, it is likely that there are at least two generations of cobaltite. Reference to Plate 53 indicates that the gold occurring within the cobaltite has a characteristic arcuate disposition which strongly suggests that infiltration has taken place. The surrounding matrix in such cases is invariably rich in gold. Jones (1937-38) found gold in similar circumstances in a specimen of Main Reef Leader (East Rand) from Government Gold Mining Areas, which was very rich in gold and contained much cobaltite. One fragment of cobaltite measured 2 x 1.75 inches. The above author ascribed an epigenetic origin to the cobaltite in this area, and concluded that some of the gold in this part of the reef is, therefore, also of an epigenetic origin. Mendelsohn (1933) described epigenetic cobaltite in a vein from the East Rand. Well-formed crystals of cobaltite have, on occasions, been seen in pebbles.

Rounded grains of cobaltite belong to the primary phase of mineralization, and have possibly been derived from the destruction of cobaltite- and uranium-bearing veins. The secondary cobaltite has probably resulted from the remobilization of original rounded grains, and belongs to the third phase of mineralization, related to the redistribution of the bulk of the gold.

(h) Gold

Gold is one of the rarest constituents of the blanket, being present to the extent of about 5 dwts., or less, to the ton, or about 0.0008%. The mineral is a very minor constituent of the samples studied, being observed in about half the polished sections examined. In the Main Reef Leader, there appears to be a definite tendency for the gold to be more concentrated along footwall contacts. This is not the general rule, however, in the other two reefs examined. No gold was noted in any of the footwall or hangingwall horizons under examination.

The gold exhibits no peculiarities in optical properties, and generally appears to have a fairly constant composition with regard to silver content. The fineness of Witwatersrand gold seldom exceeds 925 parts per thousand, and is rarely under 860 parts per thousand. In general, it can be said that the silver content is in the order of about 10%. Most of the gold examined is very finely distributed, and invisible to the naked eye, ranging from 0.001 to 0.075 mm., with much of it below 0.04 mm. Visible gold is usually found only in free-milling or oxidized blanket, where it generally occurs in irregular grains. Visible gold may also be seen at times along footwall contacts, especially in the Main Reef Leader, or in samples very rich in thucholite. Microscopic examination shows that most of the grains are very irregular in outline, and in their present state have obviously undergone varying degrees of recrystallization and remobilization. In this form, the gold has been termed hackly, a word that is used extensively on the Witwatersrand. These hackly grains, which constitute the bulk of the gold studied, usually occupy positions within the fine-grained matrix of the reef. Rounded grains of gold within the matrix, although very rare, have been observed (see Plate 54). From the plate, it can be seen that the grain is succumbing to replacement by quartz, but the original outline is demarcated by a line of inclusions. It is possible that these

rounded grains have retained their original shape, and that they were originally rounded by sedimentary processes. Liebenberg (1955) described the plucking of rounded grains of gold from polished sections of Witwatersrand blanket. Irregular grains or flakes of gold are sometimes found lying along bedding planes, or plastered over slickensided surfaces.

Gold in particularly rich samples is most commonly associated with pyrite, usually of the crystalline variety, which it may replace extensively (see Plate 39). Porous pyrite nodules are exceedingly susceptible to the infiltration of gold, especially when the surrounding matrix is rich in the latter mineral (see Plate 37). In such cases, the metal appears to have diffused inwards from large masses in the matrix, and surrounds individual pyrite grains within the porous nodule. The depth of penetration is, according to Ramdohr (1959), of the order of about .2 mm. There appears to have been a second generation or remobilization of pyrite, after the infiltration of the gold, which has given the originally porous nodule a compact appearance. Gold occurs in some grains of cobaltite (see Plate 53) in a similar manner, and probably originated by a comparable process. The mobility of the metal is also demonstrated by hair-like veinlets which penetrate pyrite grains, and cracks in minerals such as zircon. Irregular masses of gold can, in some cases, be seen surrounding detrital quartz grains, and infiltrating into rosettes or clumps of chloritoid crystals, as well as other crystalline material within the matrix (see Plate 55). In other instances, porous siliceous nodules appear to be the host.

The close association of a fair amount of the gold with skutterudite and, less frequently, linnaeite, is rather characteristic. Plate 57 shows the usual type of relationship. In other cases, roughly oval masses of gold are surrounded by narrow rims or crusts of skutterudite (see Plate 56). It appears as though the gold originally had the disposition of a nodule. The skutterudite generally surrounds the gold, and appears to be slightly younger in age, but examples of gold surrounding skutterudite are not wanting. In any event, the mobilization of skutterudite and gold took place more-or-less contemporaneously, at a very late stage, and both minerals can be seen cutting through fractured grains of crystal pyrite (see Plate 57).

The close association of gold with thucholite and, more especially, uraninite has been discussed previously. Gold is sometimes found within grains of leucoxene, and the porous structure of this mineral appears to have acted as an efficient trap for the remobilized metal. In a few cases, large portions of leucoxene grains may be occupied by gold (see Plate 58). Grains of gold may be found within massive pyrrhotite, and in such cases are fairly regular in outline. It appears, in some instances, that the rounded edges of some of these grains have been preserved by the surrounding sulphide.

Gold is rarely encountered in pebbles, and, where it does occur, is invariably of secondary origin, having migrated into the pebbles. The lack of gold in quartz pebbles has been used as an argument for the hydrothermal origin of the metal, but, as pointed out by Ramdohr (1959), many gold-quartz veins have such coarse textures that any rough treatment in a placer would result in the liberation of gold from the quartz.

In its present form, most of the gold appears to have undergone recrystallization and redeposition. There is, however, some evidence of rounded grains of gold within the matrix, especially where the surfaces of grains have been protected by later sulphides, such as pyrrhotite. The gold is considered as having been an original detrital mineral. The irregular shape of most of the grains is explained by the ductile character of the mineral. Even though it is probably chemically more stable than the uraninite, it is unlikely that it would have retained its original form under thousands of feet of rock. Hard detrital minerals, such as uraninite, pyrite, arsenopyrite, zircon, and chromite would, on the other hand, tend to break cataastically under the pressure, rather than be redistributed.

It seems unlikely, from the sporadic association between gold and pyrite, that the two minerals were deposited simultaneously from hydrothermal solutions. In nearly all cases, the remobilization of the gold belongs to a distinctly younger phase of mineralization than the second- (crystalline) generation pyrite. In some cases, however, there is evidence of the deposition of gold before the main phase of the formation of second generation pyrite. The gold is often associated with a number of minor sulphides, such as pyrrhotite, chalcopyrite, galena, skutterudite, and linnaeite, which were remobilized and redistributed in a similar way, and more-or-less contemporaneously with the gold. The origin of these sulphides and their association with gold is difficult to explain, as there is little evidence indicating that they came into the conglomerate as original detrital particles. In the samples studied, gold is fairly commonly associated with the sulphide skutterudite, which is of about the same age (see Plate 57), or, at times, younger than the gold (see Plate 56). In the case of Plate 57, gold and skutterudite, contemporaneous in age, are seen cutting through second-generation crystalline pyrite which had already succumbed to fracturing. Liebenberg (1955) believed that the close association between gold and thucholite is due to the precipitating effect of the latter mineral on gold from solutions. Whereas this may be true in some areas of the reefs under examination, it seems likely that, in a number of cases, the association of gold with thucholite is merely a reflection of the original association of gold with uraninite which was subsequently replaced or invaded by hydrocarbon during the process of thucholitization. This means that a certain amount of the gold was redistributed at, or before, the time of the formation of the thucholite (see Figure 2). This is in accordance with the observations relating to the redeposition of some of the gold before the formation of second-generation pyrite.

In general, it can be said that the main phase of remobilization of gold took place at a late stage in the ore-mineral paragenetic sequence, and that remobilization and redistribution took place more-or-less continuously. Remobilization or redeposition of the gold, which is attributed to metamorphic agencies, generally took place over very limited areas. For example, where the mineral was originally concentrated at the base or footwall contact of a reef horizon, the main concentration still lies there.

(i) Pentlandite

Pentlandite occurs, on a very minor scale, in all the reefs studied. The mineral is almost invariably restricted to the pyrrhotite, and, if it occurs as discrete particles in the matrix, it is usually in close proximity to pyrrhotite. It seems likely, therefore, that the pentlandite is an exsolution product of the pyrrhotite. The mode of occurrence and associations of the mineral have been discussed previously, in connection with pyrrhotite.

(j) Gersdorffite

Gersdorffite is very limited in its distribution, and was only noted in a few samples. The mineral is very erratic in its occurrence, and the content varies significantly even over a few inches of reef. No gersdorffite was noted in the Main Reef, and the mineral was not observed in any of the footwall or hangingwall horizons examined. The mineral is recognized by its white colour, high reflectivity, and lack of anisotropism, and its presence was confirmed by X-ray analysis. Large irregular masses are most common, and the secondary nature of the material is quite clear from its mode of occurrence. There is a definite tendency for concentration along footwall contacts, and large irregular masses are sometimes seen surrounding rounded, as well as crystalline, pyrite grains and other heavy mineral constituents (see Plate 59). Some of the gersdorffite probably originally consisted of rounded detrital grains, but a large part of it appears to be reconstituted material of obscure origin. The phase of remobilization corresponds roughly to the phase of the remobilization of most of the gold.

(k) Skutterudite and Linnaeite

As pointed out earlier, a common associate of gold, particularly in rich portions of reef, is skutterudite. The mineral was noted in all the reefs studied. Linnaeite is always subordinate to skutterudite. The optical properties of the two minerals are very similar, making distinction between the two difficult. Slight colour differences, as well as the use of a filter, however, made the distinction possible. As in the case of sulphides such as chalcopyrite and sphalerite, the origin of the skutterudite and linnaeite is very problematic. In their present form, the formation or remobilization of the minerals is clearly related to the main phase of gold mineralization (see Plates 56 and 57). Whether the minerals resulted from the remobilization of original detrital components, or whether they represent newly-formed minerals, as a result of metamorphism acting on some suitable material, is difficult to say.

(l) Galena

Galena, associated with the uraniferous components of the reefs studied, is a fairly widespread constituent. The mineral is almost invariably closely associated with uraninite grains, but irregular grains, unrelated to uraniferous components, have been observed. In most cases, the formation of galena is attributed to the reconstruction of radiogenic lead, produced mainly from the radioactive decay of uraninite. The mineral is most commonly associated with uraninite and thucholite, in the form of small veinlets, crystalline individuals, and a mere dusting. The mineral is often closely associated with pyrrhotite, which often surrounds uraninite grains. The mobility of the material is demonstrated, in some areas, by hair-like veinlets, cutting through fractured minerals, such as zircon. On the assumption that the galena is of radiogenic origin, it is possible that the formation of lead from radioactive decay must have taken place continuously over a long period. When this lead was reconstituted to form galena, from sulphur-bearing gasses or solutions, however, cannot be determined. It seems likely that most of the galena was formed at about the same time as the main phase of gold mineralization.

(m) Sphalerite

Sphalerite is an exceedingly rare constituent of the reefs studied. The relationships of sphalerite with other minerals in the Bastard Reef at the Rose Deep Mine indicate that it is completely xenomorphic, and has about the same age relationship as chalcopyrite and pyrrhotite. On the assumption that the FeS content of an FeS-ZnS-mix crystal is dependant on temperature, Fuller (1958a) showed that the temperature of formation of sphalerite in the Bird Reef Group averages 450°C. This temperature is greater than can be attributed to depth of burial alone. The suggestion was put forward that the formation of sphalerite occurred during the period of igneous activity to which the Ventersdorp dykes belong. It is assumed that the extrusion of the Ventersdorp lava was accompanied, or preceded, by emanations of volatile constituents which permeated the sediments, and which were responsible for redistributing metals previously concentrated by sedimentary processes.

(n) Millerite

Millerite was rarely encountered in the reefs under investigation. Ramdohr (1959) reported small millerite crystals in porous pyrite nodules. He considered the mineral to be of great significance, and contended that it is the immediate source of nickel for the pentlandite. Mendelsohn (1944) described very thin, pale brassy-coloured crystals of millerite in sericitized quartzite, and Cooper (1923) drew attention to a practically pure nickel sulphide found in a cavity in the Main Reef Leader (East Rand). One definite mass of the mineral, .5 mm. across, was observed in a fractured pebble.

The mineral has strong anisotropism, from pale yellow to pinkish-purple, and pleochroism from yellowish-pink to pinkish-yellow. Two varieties are present, one in the form of compact grains, and the other in the form of more porous material, composed of minute needles which surround the compact material (see Plate 60).

F. PARAGENESIS OF THE ORE MINERALS

The complexity and uniqueness of the mineralization of the Witwatersrand bankets make the drafting of a paragenetic chart (Figure 2), in the normal sense, very difficult. Most such charts are used to depict graphically the sequence of ore mineral deposition in mineral deposits of known hydrothermal origin. These charts are usually divided into two sections, the first representing the hypogene, or primary, phase of hydrothermal mineralization, and the second, the supergene phase of secondary enrichment and reconstitution of the primary minerals. There is little doubt that, in the case of the ore minerals in the basket, "hydrothermal" or "pseudo-hydrothermal" processes, induced as a result of metamorphism, have been largely responsible for the remobilization and reconstitution of most of the minerals present, and a number of distinct phases of mineralization can be recognized. It is for these reasons that a paragenetic chart has been made, similar to those normally used for illustrating the sequence of ore mineral deposition in hydrothermal deposits, but adjusted to fit the requirements of depicting the history of the ore minerals in the basket. Use has been made of the work of Liebenberg (1955) and Ramdohr (1959) in compiling this chart. It should be stressed from the outset that the hydrothermal effects referred to have nothing to do with the origin of the ore minerals in the basket, and the chart merely shows graphically the abundance of particular mineral species, as they are seen now, related to one of the phases of mineralization shown in the chart. For example, gold has been depicted in the chart as being of a late stage in the mineralization history, but this does not imply that the mineral is hydrothermal in origin. It merely indicates that, in its present form, most of the gold appears to be a late-stage mineral in the sequence of reconstitution. The intensity of the lines shown on the chart (Figure 2) indicates approximately the volume percent of a particular mineral species, as it is now seen to occur in the rock. The chart has been divided into three arbitrary groups which appear to represent most clearly the mineralization history of the basket.

The first phase of mineralization (1) shown on the chart represents mineral constituents which, in their present form, appear to be detrital in origin. In this group are included most of the rounded grains of arsenopyrite, glaucodot, uraninite, and most of the rounded grains of pyrite. Rounded grains of gold representing detrital particles are rarely found, and it is questionable whether the other mineral constituents shown on the chart were originally of detrital origin.

The second phase of mineralization (2) represents the main period of crystalline pyrite formation, of both the compact and porous varieties. It is believed that most of this pyrite was derived from original rounded grains, probably during a period of metamorphism. It is likely that remobilization of many of the other constituents took place at this time, but that they underwent subsequent remobilization, and in their present form represent a later phase of remobilization or recrystallization. There is evidence of remobilization and, possibly, recrystallization of minerals such as uraninite, gold, galena, and, to a lesser extent, arsenopyrite, thucholite, and pyrrhotite contemporaneously with the crystalline pyrite. This mineralization is insignificant, however, compared to the excessive development of crystalline pyrite during this phase. Ramdohr (1959) recognized a definite phase of secondary, crystalline, or hydrothermal, pyrite formation. The formation of this pyrite is distinctly older than the main phase of remobilization and redeposition of gold. Two phases of redeposited gold have been identified. An older generation is contemporaneous with the crystalline or secondary pyrite, and is sometimes seen coating original rounded pyrite grains, and is closely

associated with the secondary pyrite empacted on these grains. This gold is difficult to distinguish from the younger generation of gold referred to, and generally occurs in minor amounts. Ramdohr (1959) stated that : "The formation of idiomorphic pyrite is contemporaneous with the deposition of the older generation of gold, but, in spite of this, intergrowths of the two, proving this relation, are not common". Reference to the plates showing crystalline pyrite clearly indicate that this form of the mineral is distinctly older than most of the other sulphides and gold.

The third phase of mineralization (3) is related to the period when most of the gold was remobilized, redistributed, and redeposited, probably under conditions of metamorphism, and it is clearly younger than the second phase of crystalline pyrite formation. All the minerals, to a greater or lesser degree, excepting arsenopyrite and glaucodot, are represented in this group, and a number of mineral species, such as linnaeite, skutterudite, sphalerite, and pentlandite (of exsolution origin), not present in the first or second phases, make their appearance. The origin of most of the latter minerals is obscure, but it seems likely that they may have been reconstituted from original detrital components. The secondary nature of most of the minerals represented in the third phase has been stressed by many workers. Liebenberg (1955), for example, has demonstrated the secondary nature of gold, in its present form, in Witwatersrand banket. According to Ramdohr (1959) : "It is quite plain that the gold in its present form is in most cases younger than the secondary growths of clear pyrite". In addition, Liebenberg (1955) has clearly shown that a second generation of uraninite exists, which is, in most cases, younger than the crystalline pyrite. The secondary nature of both galena and thucholite have also been established. Ramdohr (1959) studied the age relationship of the various ore minerals, and concluded that most of the rare sulphides were deposited contemporaneously with the main phase of redeposition of the gold. Indications are that thucholite may, in part, be earlier than the second-generation pyrite. In most cases, however, the thucholite appears to be younger than the crystalline pyrite. For the most part, pyrrhotite seems to be contemporaneous with minerals such as chalcopyrite and sphalerite, which show mutual boundary relationships, and are clearly related to the main phase of redeposition of the gold. Skutterudite and linnaeite are contemporaneous with the main phase of remobilized gold. Pyrite, other than hair-like veinlets and material formed by supergene processes from pyrrhotite (Ramdohr, 1959), is rare in the third phase of mineralization.

THE DISTRIBUTION AND ORIGIN OF THE COMPONENT MINERALS

It has been known for a long time that the mineral content, structures, and textures of the various conglomerates throughout the Witwatersrand System are similar. It is for this reason that correlation of reef horizons by mineral content alone has, as far as the writer is aware, never been attempted. In the present investigation, insufficient samples were examined to indicate absolute and indisputable differences in reef horizons from a purely qualitative mineralogical point of view.

From a qualitative examination of thin-sections, the most obvious difference between the Main Reef and Main Reef Leader (East Rand) lies in the phyllosilicate content. Chloritoid appears to be the most important of these, as far as an aid to comparison of reef horizons is concerned. Whereas all the thin-sections of Main Reef and Main Reef Leader studied contain chloritoid, to a variable degree, no sign of the mineral, whatsoever, was found in thin-sections of the Main Reef Leader (East Rand). The main phyllosilicates in the last-mentioned reef consists of chlorite and sericite. Examination of thin-sections of South Reef from five mines in the Central Rand area indicated that, although present, chloritoid occurs in very minor amounts as compared to chlorite and sericite. From the above it is concluded that, as far as the chloritoid content of the matrix is concerned, the Main Reef Leader (East Rand) has more

affinities with the South Reef of the Central Rand than with the Main Reef or Main Reef Leader of the Central Rand. It should be borne in mind that, if different sources of reef material were present, then the composition of the matrix might be different, even though the reefs are contemporaneous.

In addition to a variation of the chloritoid content from reef to reef, there may be variations in the chloritoid and chlorite content within a particular reef horizon. This is especially marked in the case of the Main Reef, where chloritoid crystals occur in profusion in the matrix of the reef in the mines of the Krugersdorp area of the West Rand. In this section, chloritoid occurs almost to the exclusion of chlorite and sericite. In easterly and southerly directions from this point, the chloritoid content of the reef diminishes, and there is a corresponding increase in the chlorite content. By the Doornfontein and West Driefontein mines in the south, and the Rose Deep and E.R.P.M. mines in the east, the chloritoid content of the reef has dropped to a very low figure, and chlorite is the main phyllosilicate. The sericite content remains fairly constant throughout this area. As chloritoid is a fairly sensitive indicator of composition, rather than of temperature or stress (Halferdahl, 1961), it is concluded from the above that the composition of the interstitial matrix mud of the Main Reef in the Krugersdorp area was suitable for the formation of chloritoid, and that this composition changed progressively in southerly and easterly directions where conditions were more conducive to the formation of chlorite. The observed changes in the phyllosilicate content may be explained by the fact that the interstitial mud in the vicinity of an assumed entry point was rich in compounds such as Al_2O_3 and FeO , necessary for the formation of chloritoid. Pettijohn (1957) considered it possible that the more aluminium-rich muds are concentrated near shorelines. In addition, there appears to be a progressive increase in potash and magnesia in muds, with increasing distance from shore. This could be reflected in the increase in the chlorite content towards the centre of the basin. It is tentatively suggested that this pattern is a manifestation of the fact that an entry point of reef material existed somewhere in the vicinity of Krugersdorp.

From a purely qualitative point of view, the matrix of the Main Reef Leader (East Rand) is distinctly more sericitic than the matrix of either the Main Reef or Main Reef Leader. The generally sericitic nature of the Main Reef Leader (East Rand) is probably an indication of the composition of the rocks in the source area. It is envisaged that the original interstitial mud must have been relatively rich in compounds such as Al_2O_3 and K_2O and relatively poor in iron-rich compounds.

A heavy mineral examination, mainly with the aid of Ultrapak illumination, has shown that zircon, chromite, and leucoxene are the main heavy minerals in the reefs under investigation. Although variations in the content of these three mineral species are not at once obvious, it is apparent that chromite is more abundant in the Main Reef Leader (East Rand) and the Main Reef of the West Wits Line than in the Main Reef and Main Reef Leader of the Central Rand. It is contended that these differences may be an indication of different source rocks, and therefore an indication of different sources of reef material. Although most of the leucoxene grains examined are in a highly altered state, it is concluded from mineralogical evidence that the detrital mineral which gave rise to the material was either sphene or ilmenite, or probably both. Radioactive sphene may have been responsible for the production of radioactive leucoxene.

The uncertain origin of many of the ore minerals occurring within the reefs studied has made reef correlation, on the basis of ore mineral content, very difficult. The most apparent differences in the ore mineralogy of the reefs under investigation lies in the pyrrhotite content. Whereas the Main Reef Leader (East Rand), and the Main Reef Leader contain large, but erratic, amounts of pyrrhotite, especially the former reef, the Main Reef is singularly free of the mineral. It would seem likely from a first appraisal, therefore, that conditions conducive to the formation of pyrrhotite were not present in the Main Reef horizon. The only pyrrhotite in the latter reef is present in the form of minute flakes and veinlets, often associated with grains of uraninite.

It is highly unlikely that a mineral such as pyrrhotite can be used as a basis of reef correlation. This is mainly because the conditions necessary for its formation are so varied. It is believed that processes such as the dissociation of pyrite, stresses within reef horizons (often indicated by quartz-filled pressure shadows), and the proximity of basic intrusions are responsible for the formation of the mineral. It is clear that these processes took place after the deposition of the reef horizons, and that the formation of pyrrhotite was, therefore, governed by local conditions.

According to Ramdohr (1959), pyrrhotite is limited to regions that were originally very deep and were heated up in some manner. All the reefs studied in the present investigation occur at depth, yet only the Main Reef Leader (East Rand) and Main Reef Leader contain relatively large amounts of pyrrhotite. Depth of burial alone, therefore, does not appear to be a prerequisite for the formation of the mineral. It seems likely that the formation of pyrrhotite through dissociation of particularly reactive pyrite, i.e. the variety with an open texture (Ramdohr, 1959), could explain the observed distribution of pyrrhotite in the Main Reef Leader (East Rand) and the Main Reef Leader. In the case of the latter reefs, it is probable that open-textured pyrite resulted from the tectonic fracturing of rounded and crystalline material. There is abundant evidence of stress, particularly in the form of pressure shadows and crenulation folds, which could have resulted in the large-scale fracturing of pyrite and other constituents. It is thought that the influence of intrusives in producing pyrrhotite was locally restricted. In the case of the Main Reef, it may be concluded therefore that the pyrite did not have a suitable open texture conducive to the formation of pyrrhotite. This, in turn, suggests that tectonic forces acting on the horizon were not of sufficient magnitude to produce large-scale fracturing of the pyrite.

In addition to the relatively large percentages of pyrrhotite which they contain, the Main Reef Leader (East Rand) and the Main Reef Leader contain a fairly wide variety of ore minerals not found in the Main Reef. Minerals commonly encountered in the former reefs, but rare in the Main Reef, include thucholite, chalcopyrite, cobaltite (secondary variety), and gersdorffite. The only mineral, excluding pyrite, which occurs relatively constantly throughout all the reef horizons studied is arsenopyrite (plus glaucodot and cobaltite) of the rounded variety. Arsenopyrite appears to be more plentiful in the Main Reef Leader (East Rand), and in the Main Reef of the West Wits Line. The mineral is rare in the Main Reef and Main Reef Leader of the Central Rand. Although generally occurring erratically in smaller amounts, uraninite is a fairly widespread constituent of the reefs studied.

It is apparent from the above, that besides a general appraisal, no definite conclusions can be drawn, regarding reef correlations or reef characteristics, from qualitative mineralogical observations alone. As a result, resort must be made to a quantitative approach in an attempt to correlate and classify reef horizons by their mineralogy.

A detailed examination of the ore minerals in the reef horizons under discussion has led to the conclusion that, in most cases, these minerals have been derived from detrital constituents in the conglomerate. Those minerals which have retained their original characteristics include arsenopyrite, glaucodot, uraninite, cobaltite, pyrite, and, in rare cases, gold. Subsequent metamorphism produced abundant crystalline pyrite, which was followed by the main phase of remobilization and redeposition of gold, contemporaneously with a large variety of other minerals including skutterudite, linnaeite, sphalerite, chalcopyrite, galena, gersdorffite, pyrrhotite (plus exsolution pentlandite), thucholite, cobaltite, and uraninite (secondary variety). The origin of these latter minerals is obscure, but it seems probable that most of them have been derived directly or indirectly from original detrital components of the conglomerates. The effect of basic intrusions on the ore mineralogy is thought to be significant only over very localised areas of reef.

It seems apparent from the relative consistency of the paragenesis of the ore minerals in all the reefs under examination that some definite event, or events, during the geological history of the area must have been responsible for the remobilization, redistribution, recrystallization, and reconstitution of the ore minerals. It is apparent that these processes could only have taken place under conditions of metamorphism and reheating. The depth of burial of the rocks could have ensured metamorphic conditions capable of remobilization of constituents, but the definite phases of mineralization referred to earlier seem to be the result of one, or several, peaks of heating up. The most obvious and commonly cited post-Witwatersrand geological events which could have given rise to these peaks are the outpouring of the Ventersdorp volcanics, the emplacement of the Bushveld Igneous Complex and the intrusion of Karroo dolerites. Although all these geological events probably played a part in the remobilization and recrystallization of the ore minerals, no decisive criteria exist indicating this, as pointed out by Ramdohr (1959). It seems probable, from their close association with the Witwatersrand System, that the Ventersdorp volcanics were mainly responsible for the formation of the second generation of pyrite, and to a certain extent, the remobilization and reconstitution of the secondary sulphides. It is believed that the metamorphic effects produced subsequently by depth of burial were mainly responsible for the last phase — the redistribution of gold and the rare sulphides, which were possibly more susceptible to remobilization than the previously formed crystalline pyrite. It is thought that the effect of the Bushveld Igneous Complex on the paragenesis of the ore minerals was negligible, and that Karroo intrusives were responsible for mineralogical changes only on a very limited scale.

The origin of some of the ore minerals is problematic. The patchy occurrence of thucholite within the reefs studied, for example, is difficult to reconcile with a detrital origin. The widespread occurrence of the material in the conglomerates seems to preclude the possibility of the hydrocarbon having been introduced from external sources. It is thought likely that the material may originally have resulted from primitive organic life which existed in certain parts of the depositional depressions. It is probable that this primitive life reached its optimum development under special conditions associated with some of the conglomerate horizons. Stagnant environments prevailing in fluvial or deltaic flats were most conducive to its formation, after the main influx of reef material. Migration of hydrocarbons, derived from this material, subsequently took place, and resulted in the thucholitization of detrital uraninite grains where these were present in the reef horizon. The origin of minerals such as skutterudite, linnaeite, and other rare sulphides, sometimes associated with gold, is hard to explain, but it is thought likely that they resulted from the reconstitution of earlier detrital material, with the addition of sulphur.

The preferential association of gold with uraninite and thucholite has been discussed by a number of workers. In addition, Ramdohr (1959) and Liebenberg (1955) have mentioned the association of small amounts of pyrrhotite and chalcopyrite with uraninite. In the latter cases, the heat produced by the radioactive decay of the uraninite may have resulted in the conversion of small amounts of pyrite, in close proximity to the uraninite, to pyrrhotite. The preferential association of gold with uraninite is possibly explained by the fact that the radioactive decay and cataclastic shattering of the uraninite grains have resulted in relatively porous grains more suitable for the infiltration of gold than less porous constituents such as chromite and zircon.

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KEY TO FIGURES

- Figure 1 : Locality map showing mine boundaries and approximate sampling positions. (Key to numbers of mines given in text of paper).
- Figure 2 : Paragenetic chart depicting the sequence of ore mineral deposition in the Main Reef and Main Reef Leader, as developed in the West Wits Area, West Rand, Central Rand, and East Rand.
- Figure 3 : Two idealized sections of the Main Reef Leader (East Rand) at Modder East Mine, showing the ore mineral content of selected samples, in relation to gold content.

* * * * *

KEY TO PLATES

- Plate 1 : Rose Deep Main Reef
Grains of alloigenic quartz occurring within a chloritic matrix.
Magnification $\times 62.5$.

Plate 2 : Marievale Main Reef Leader (East Rand)

Pyrite of the compact crystalline variety replacing subangular allogenic quartz grains of the matrix. Note the porous nature of the large pyrite crystal at the upper right hand corner of the plate. Magnification $\times 62.5$.

Plate 3 : Crown Mines Main Reef Leader

Delicate rutile and leucoxene frameworks formed from the titanium-bearing portion of original grains of titanium magnetite. Magnification $\times 62.5$.

Plate 4 : E.R.P.M. Main Reef Leader

Zoned zircon grain enclosed within a quartz pebble. Crystal edges are well preserved, except where corrosion has taken place. Magnification $\times 250$.

Plate 5 : Van Dyk Main Reef Leader (East Rand)

Detrital grain of radioactive zircon. The radioactive (uraniferous) zone is softer than the rest of the grain, and is characterized by numerous specks of galena (white). Magnification $\times 250$.

Plate 6 : E.R.P.M. Composite Reef

Typical grain of zircon occurring in fine-grained matrix material. The rounded pyramidal terminations, as well as the fracturing, are characteristic of these grains. The black material to the right is composed mainly of leucoxene. A chloritoid crystal can be seen to the left. Magnification $\times 62.5$.

Plate 7 : Spaarwater Main Reef Leader (East Rand)

Secondary pyrite moulded on an original, well-rounded grain of zircon. Magnification $\times 250$.

Plate 8 : Van Dyk Main Reef Leader (East Rand)

Radially fractured grain of chromite being extensively replaced by sericite. The original outline of the grain is demarcated by a discontinuous line of chromiferous material. Magnification $\times 250$.

Plate 9 : East Geduld Main Reef Leader (East Rand)

Original detrital grain of tourmaline with outgrowths of authigenic material parallel to C-crystallographic axis. The original rounded outline is faintly discernible in the upper right-hand corner of the plate. Magnification $\times 250$.

Plate 10 : Marievale Main Reef Leader (East Rand)

Small, elongated detrital grain of apatite occurring within the matrix. The grain has been fractured, and the fracture filled with sulphide. Magnification $\times 250$.

Plate 11 : Vogelstruisbuilt Main Reef Leader (East Rand)

Portion of vein quartz pebble showing characteristic type of recrystallization. Magnification $\times 62.5$. Crossed nicols.

Plate 12 : East Geduld Main Reef Leader (East Rand)

Typical banded chert pebble showing mosaic texture. The dark bands are composed of an opaque material which is possibly hematite. Magnification $\times 62.5$. Crossed nicols.

Plate 13 : Modder East Main Reef Leader (East Rand)

Quartz porphyry pebble with an angular quartz phenocryst showing slight signs of corrosion. The groundmass is composed dominantly of quartz and sericite. Magnification $\times 62.5$. Crossed nicols.

Plate 14 : Libanon Main Reef

Profuse development of columnar or fibrous quartz growing within a pressure shadow, and closely associated with a grain of pyrite. The quartz has grown from an alloigenic grain in the upper portion of the plate. Slight bending of the columns is probably due to differential lateral compression during growth. Magnification $\times 250$. Crossed nicols.

Plate 15 : Vogelstruisbuilt Main Reef Leader (East Rand)

Columnar quartz growing on adjacent sides of a rounded pyrite grain. Growth has taken place at right angles to the direction of stress which in this case is roughly from left to right. Magnification $\times 62.5$. Crossed nicols.

Plate 16 : Modder East Main Reef Leader (East Rand)

Crenulation folds developed in the Jeppestown shale which in this area forms the footwall. The axial traces of these folds run from left to right, and the closely spaced axial planes form shear cleavage. The shale consists dominantly of a fine-grained intergrowth of chlorite and sericite. Magnification $\times 62.5$.

Plate 17 : Venterspost Main Reef

Beautifully developed, "clean", columnar quartz associated with a grain of sulphide, and adjacent to quartz, also of the columnar variety, but growing between quartz grains, instead of sulphide or other resistant material. The dirty nature of the latter variety, which is probably composed mainly of remobilized silty material, is apparent. Magnification $\times 250$. Crossed nicols.

Plate 18 : Spaarwater Main Reef Leader (East Rand)

Stubby crystals of columnar quartz growing at right angles to the controlling edges of a fractured pyrite grain. Note the rectangular fragment of sulphide which has been dislodged due to the force of growth of the quartz. Magnification $\times 250$. Crossed nicols.

Plate 19 : Modder East Main Reef Leader (East Rand)

Sulphide stringers (pyrrhotite) aligned parallel to the schistosity of matrix material which has a columnar habit. Magnification $\times 62.5$. Crossed nicols.

Plate 20 : Grootvlei Main Reef Leader (East Rand)

Rounded grains of pyrite being extensively replaced along fractures by sericitic material. Magnification $\times 62.5$.

Plate 21 : Modder East Main Reef Leader (East Rand)

Compact aggregate of chlorite crystals (penninite variety). Note the well-developed cleavage. Magnification $\times 250$.

Plate 22 : Van Dyk Main Reef Leader (East Rand)

Parallel intergrowths of chlorite and sericite lining the walls of a vein. Magnification $\times 2.5$.

Plate 23 : East Daggafontein Main Reef Leader (East Rand)

Fine-grained aggregate of chlorite occupying a crack in a chromite grain. Note how the grain has been pushed apart due to the growth of the chlorite. Magnification $\times 250$.

Plate 24 : Crown Mines Main Reef Leader (Black Bar Footwall)

Profuse development of chloritoid crystals within the shale footwall known as the Black Bar. The crystalline nature of the pyrite (black) is apparent. Magnification $\times 250$.

Plate 25 : West Rand Consolidated Footwall Quartzite

Abundant crystals of chloritoid occupying the interstices between allogenic quartz grains. Magnification $\times 25$.

Plate 26 : Crown Mines Main Reef Leader

Porphyroblastic crystals of chloritoid within a mass of skeletal pyrite. Magnification $\times 62.5$.

Plate 27 : Crown Mines Main Reef Leader

Rosette of chloritoid crystals moulded on a rounded pyrite grain and a grain of leucoxene (extreme right). Note the diffuse outline of the latter grain. Magnification $\times 62.5$.

Plate 28 : Crown Mines Main Reef Leader

Typical rosette-like aggregate of chloritoid, composed of a number of discrete crystals. Replacement by quartz has commenced in the central portion of the aggregate. Abundant small sericite crystals can be seen in the surrounding matrix. Magnification $\times 250$.

Plate 29 : Venterspost Main Reef

Secondary pyrite moulded on a chloritoid crystal. Magnification $\times 250$.

Plate 30 : Crown Mines Main Reef Leader

Aggregates of chloritoid crystals being extensively replaced by authigenic quartz. Note how the replacement starts from the centre of the aggregates and moves outwards, making use of cleavage traces within the chloritoid crystals. Magnification $\times 62.5$.

Plate 31 : Van Dyk Main Reef Leader (East Rand)

Large authigenic tourmaline crystal (possibly originating from an allogenic grain), with numerous smaller crystal outgrowths. Magnification $\times 250$.

Plate 32 : Crown Mines Main Reef Leader

Rounded granule of pyrite being extensively replaced by pyrrhotite (dark grey) along two major directions. Magnification $\times 250$.

Plate 33 : Crown Mines Main Reef Leader

Porous crystalline pyrite surrounding original rounded compact grains of the same material. Magnification $\times 250$.

Plate 34 : Vogelstruisbult Main Reef Leader (East Rand)

Compact rounded grains of pyrite (some showing slight signs of re-crystallization along their margins), associated with grains of chromite (grey), zircon (small spherical grain in the right-hand lower corner), and leucoxene (light grey individuals with a pitted appearance). Magnification $\times 62.5$.

Plate 35 : Daggafontein Main Reef Leader (East Rand)

Rounded porous pyrite nodule associated with smaller compact rounded grains. Note the large size and loosely knit texture of the porous individual. Magnification $\times 62.5$.

Plate 36 : Daggafontein Main Reef Leader (East Rand)

Portion of the same porous grain of pyrite shown in Plate 35. Note the loosely knit nature as compared with the associated compact rounded grains, in addition to the characteristic octahedral crosses. Magnification $\times 250$.

Plate 37 : Geduld Main Reef Leader (East Rand)

Gold (white angular particles) infiltrated into a porous pyrite nodule. The gold is more plentiful in areas where pyrite is abundant. Magnification $\times 250$.

Plate 38 : East Geduld Main Reef Leader (East Rand)

Delicate outgrowths of compact crystalline pyrite on original grains of rounded compact pyrite. Magnification $\times 250$.

Plate 39 : Crown Mines Main Reef Leader

Typical occurrence of gold (Au), replacing the edges of a mass of compact crystalline pyrite. Magnification $\times 250$.

Plate 40 : Spaarwater Main Reef Leader (East Rand)

Zonal porous crystalline pyrite, probably grown *in situ* by the process of accretion. Magnification $\times 62.5$.

Plate 41 : Spaarwater Main Reef Leader (East Rand)

Portion of zoned porous crystalline pyrite depicted in Plate 40. The zones are defined by a series of aligned pores. Magnification $\times 250$.

Plate 42 : Rose Deep Bastard Reef

Orientated pentlandite "flames" (white), within pyrrhotite. Magnification $\times 500$.

Plate 43 : Crown Mines Main Reef Leader

Late stage in the replacement of pyrite (white) by pyrrhotite (grey). The replacement appears to have taken place along two major controlling directions. Magnification $\times 62.5$.

Plate 44 : Crown Mines Main Reef Leader

Grain of rounded pyrite (white) being engulfed by pyrrhotite (grey). Magnification $\times 62.5$.

Plate 45 : Rose Deep Bastard Reef

Pentlandite flames forming a type of herring-bone structure about a twin-plane. Magnification $\times 250$.

Plate 46 : Sub Nigel Main Reef Leader (East Rand)

Pyrrhotite (grey) containing gold (white), and cutting through and surrounding primary grains of uraninite (dark grey). The pyrrhotite, in addition to the uraninite, contains small particles of galena. A mass of crystalline pyrite can be seen at the top of the plate. Magnification $\times 250$.

Plate 47 : Crown Mines Main Reef Leader

Thucholite granule (grey, lower portion of plate) containing uraninite inclusions (light grey) and situated on the Black Bar footwall contact. The grain is associated with pyrite (Py) and chalcopyrite (Cp). A large, rounded, fractured grain of zircon can be seen in the upper portion of the plate. The tabular mineral is chloritoid. Magnification $\times 250$.

Plate 48 : East Geduld Main Reef Leader (East Rand)

Large nodule of thucholite containing isolated angular fragments of uraninite. Gold (white) is preferentially associated with the uraninite. Magnification $\times 250$.

Plate 49 : Vlakfontein Main Reef Leader (East Rand)

Large, rounded grain of arsenopyrite surrounded by pyrrhotite. Magnification $\times 250$.

Plate 50 : Libanon Main Reef

Well-preserved rhombohedral crystal of arsenopyrite occurring within a quartz pebble. Magnification $\times 250$.

Plate 51 : East Daggafontein Main Reef Leader (East Rand)

Typical grains of uraninite (the two grains in centre of plate) closely associated with specks and veinlets of gold. The sub-angular to sub-rounded outlines of the grains are apparent. The grains at the bottom and top of the plate are composed of leucoxenic material. Magnification $\times 250$.

Plate 52 : Sub Nigel Main Reef Leader (East Rand)

Extensive replacement of a fractured uraninite grain (dark grey) by gold (white) and pyrrhotite (grey). Magnification $\times 250$.

Plate 53 : Geduld Main Reef Leader (East Rand)

Irregular mass of cobaltite (Cb) containing abundant gold (Au). The arcuate shape of the gold is apparent. Magnification $\times 250$.

Plate 54 : East Geduld Main Reef Leader (East Rand)

Spherical, rounded grain of gold, which is possibly an original detrital component of the matrix. Slight replacement of quartz has taken place along parts of the margin, but the original shape is delineated by aligned inclusions. Magnification $\times 250$.

Plate 55 : East Geduld Main Reef Leader (East Rand)

Remobilized gold moulded on chloritoid crystals. Magnification $\times 250$.

Plate 56 : East Geduld Main Reef Leader (East Rand)

Oval mass of gold (Au) encrusted by a rim of skutterudite (Sk). Magnification $\times 250$.

Plate 57 : Crown Mines Main Reef Leader

Gold (Au) and skutterudite (Sk) cutting through a fractured grain of crystalline pyrite (Py). Magnification $\times 250$.

Plate 58 : Geduld Main Reef Leader (East Rand)

Gold occupying the central portion of a grain of leucoxene. This gold has probably infiltrated into the grain from the surrounding matrix. Magnification $\times 250$.

Plate 59 : Crown Mines Main Reef Leader

Rounded grains of pyrite (Py) and an angular grain of uraninite (upper left-hand corner), surrounded by gersdorffite (Ges). Magnification $\times 250$.

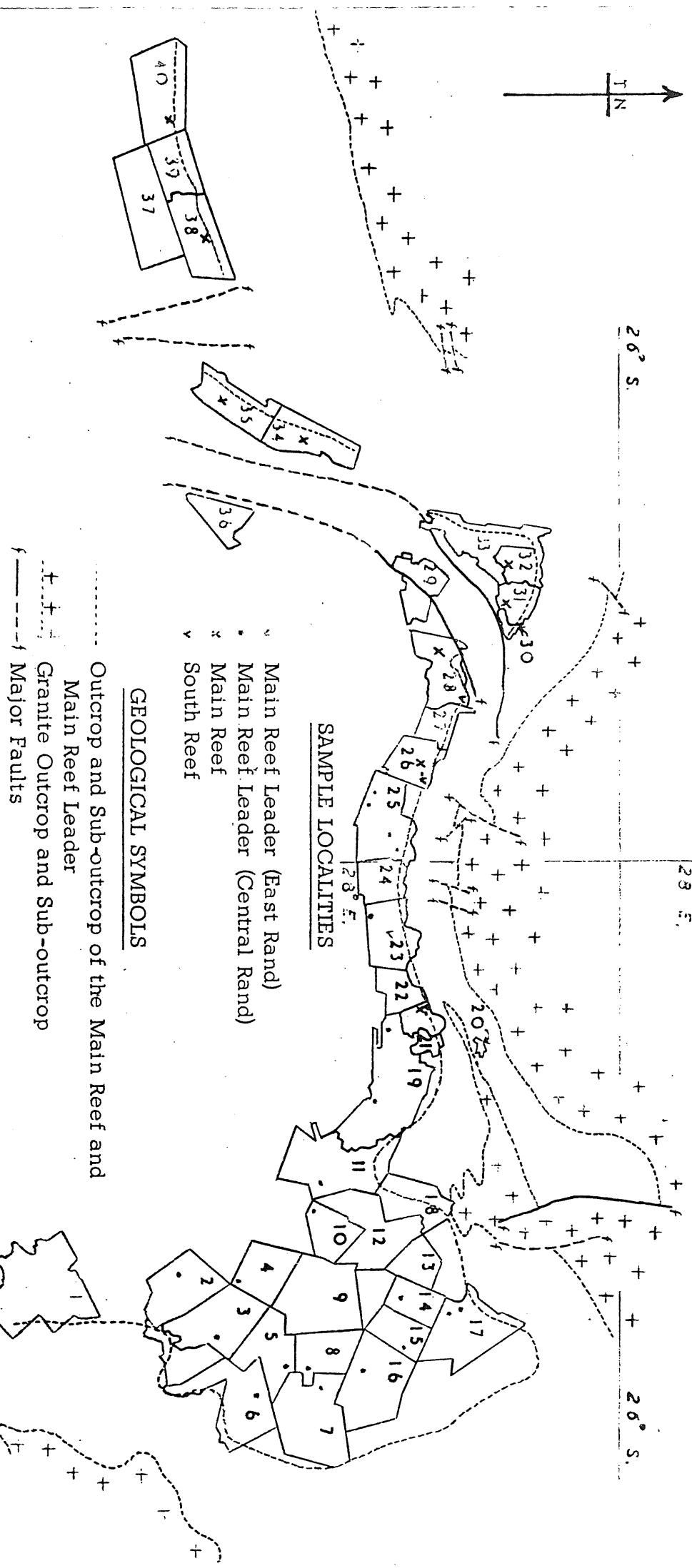
Plate 60 : Rose Deep Main Reef

Large mass of millerite occurring within the matrix. A compact variety, surrounded by a more porous variety is discernible. Magnification $\times 250$.

* * * * *

FIG. 1 : Locality Map showing Mine Boundaries and Sampling Positions

Scale 1 : 500,000



N.B. : Numbers given indicate mine properties - see accompanying sheet

Fig. 2 : Chart depicting the paragenetic sequence of ore deposition in the Main Reef, Main Reef Leader and Main Reef Leader (East Rand)
 1, indicates primary detrital components, 2, the main phase of secondary pyrite formation, and 3, the main phase of gold and most of the sulphides.

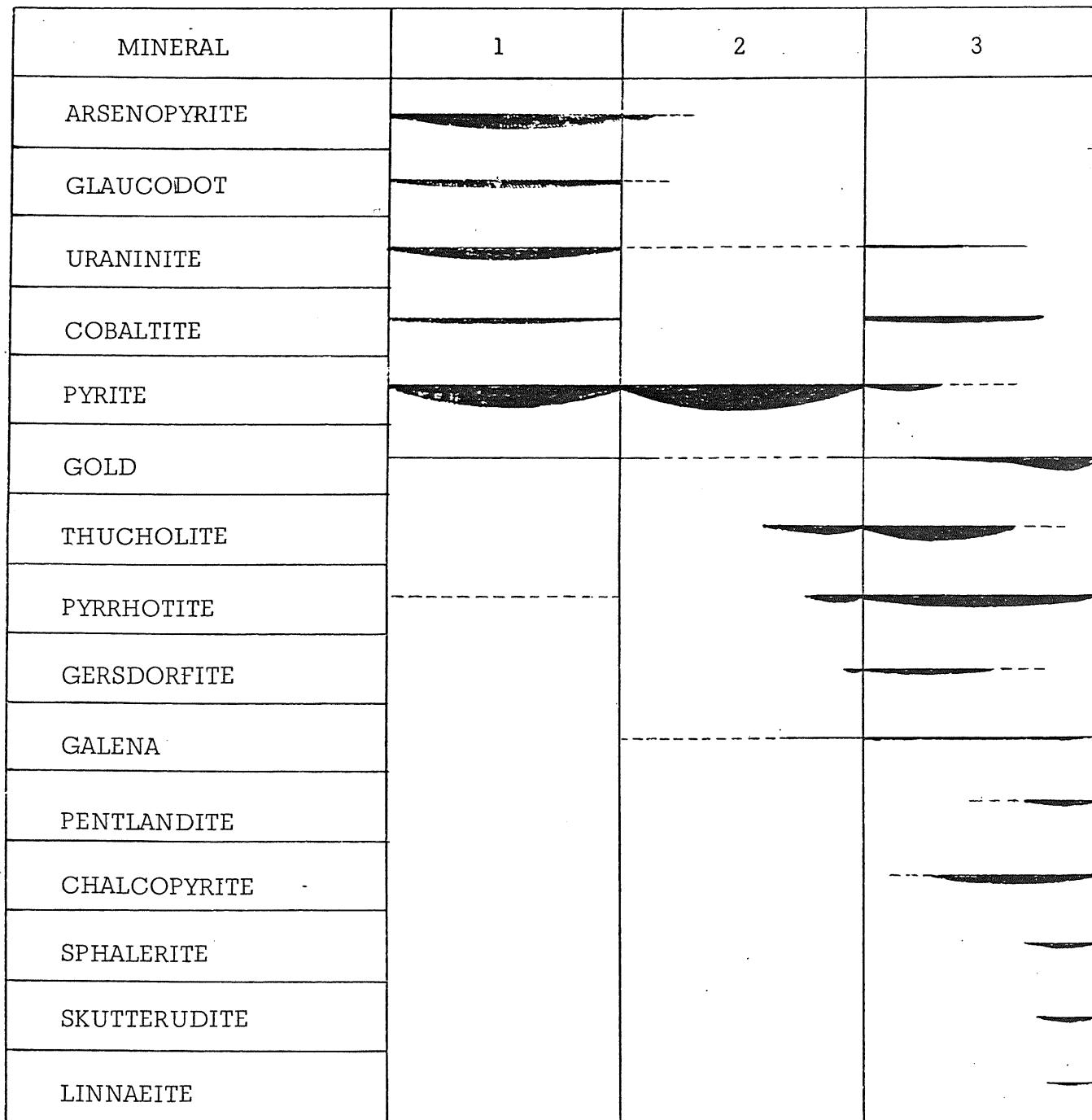


Fig. 3a

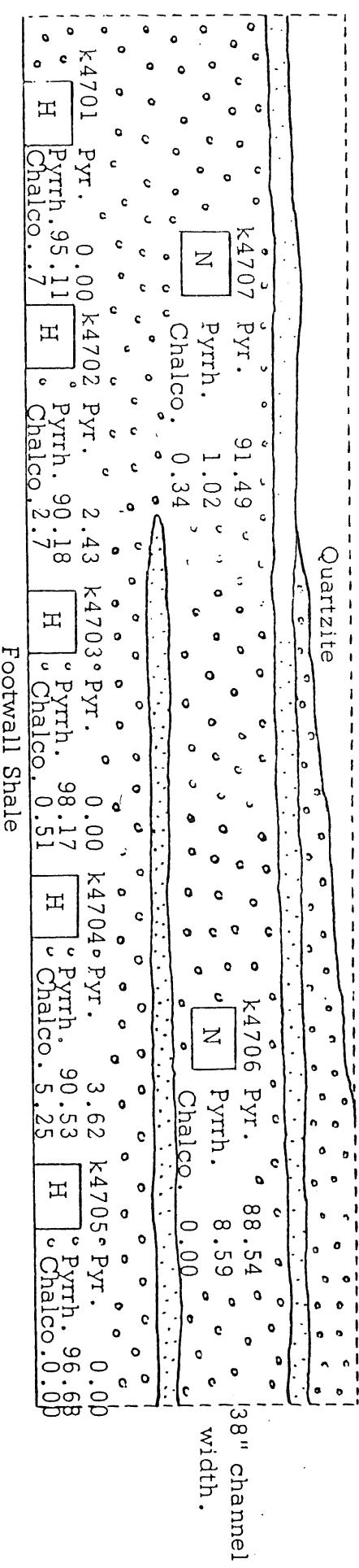
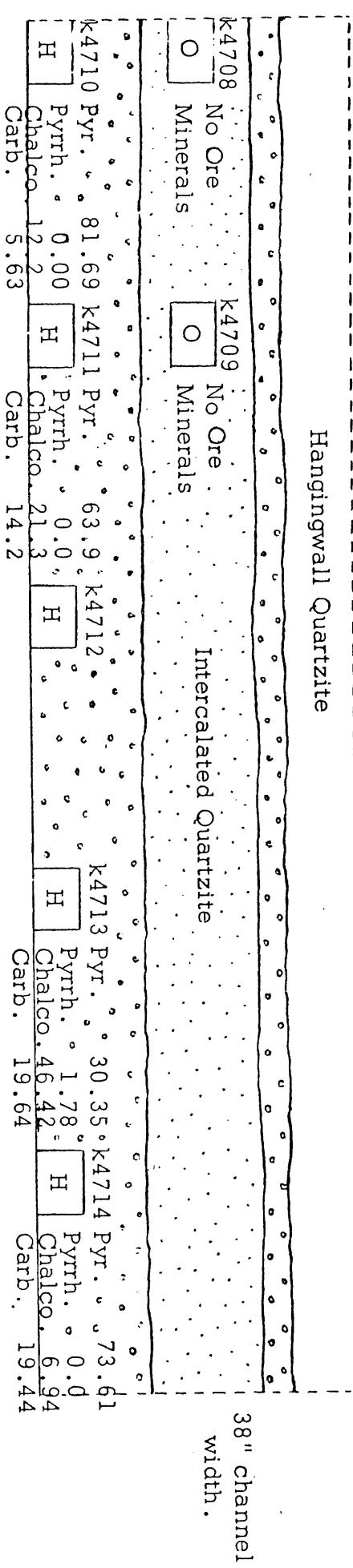


FIG. 3. Sections of Main Reef Leader (East Rand) from Modder East showing Sample Localities and the Relative Percentages of Pyrite, Pyrrhotite, Chalcopyrite and in the case of Fig. 3b. Carbon. Gold values are given in Blocks : H = high, N = normal and O = no values.

Sections of Main Reef Leader (East Rand) from Modder East showing Sample Localities and the Relative Percentages of Pyrite, Pyrrhotite, Chalcopyrite and in the case of Fig. 3b. Carbon. Gold values are given in Blocks : H = high, N = normal and O = no values.

Fig. 3b.



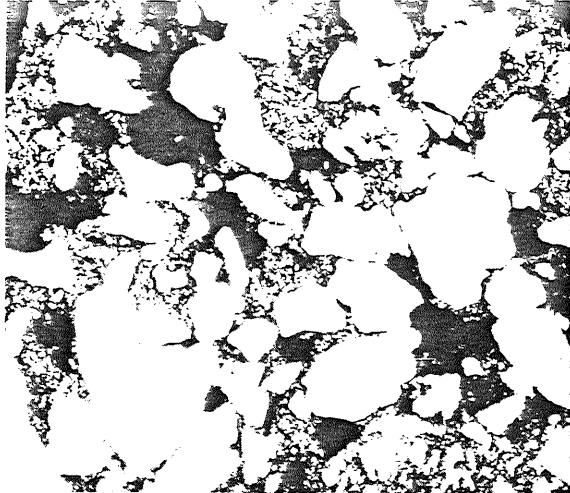


PLATE 1.



PLATE 2.

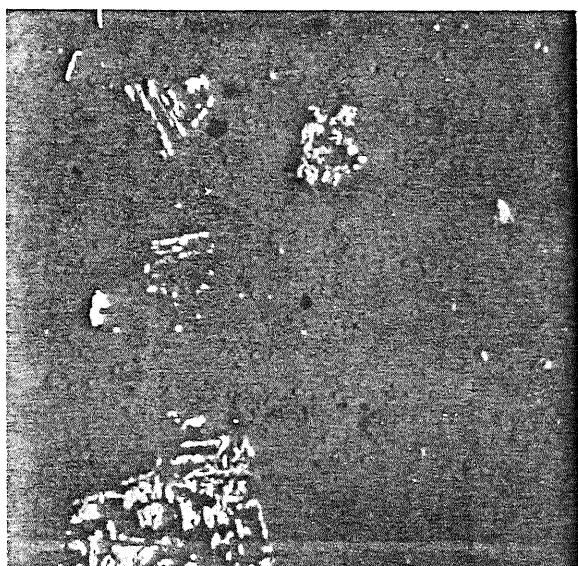


PLATE 3.



PLATE 4.



PLATE 5.

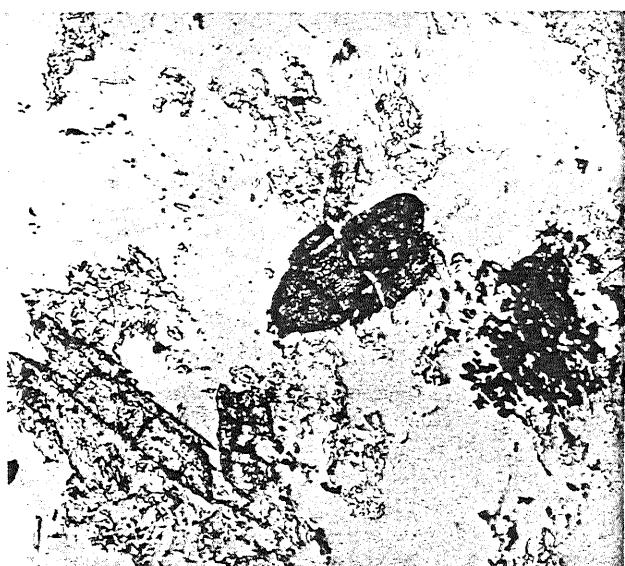


PLATE 6.

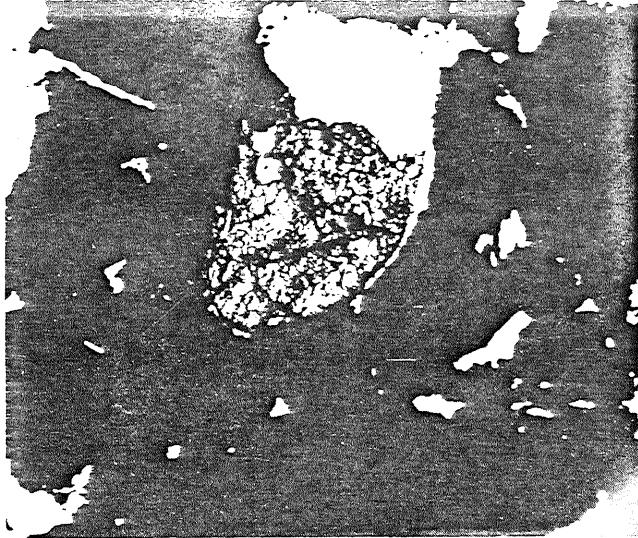


PLATE 7.



PLATE 8.

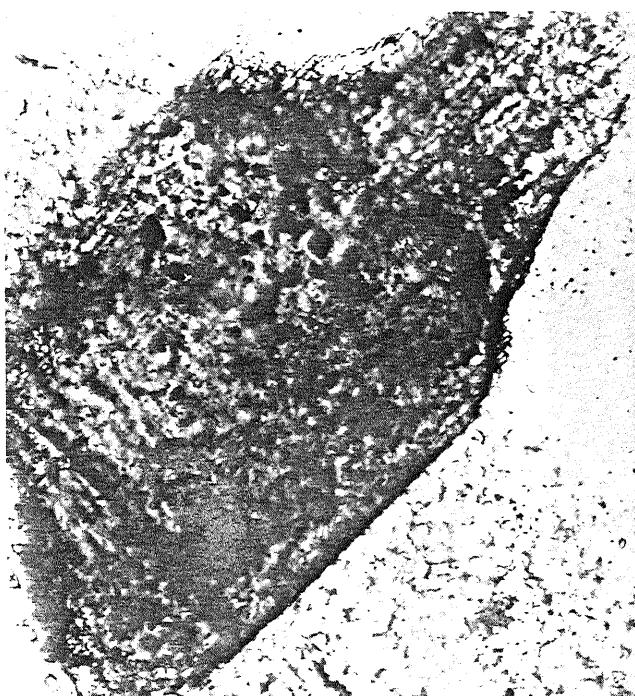


PLATE 9.



PLATE 10.

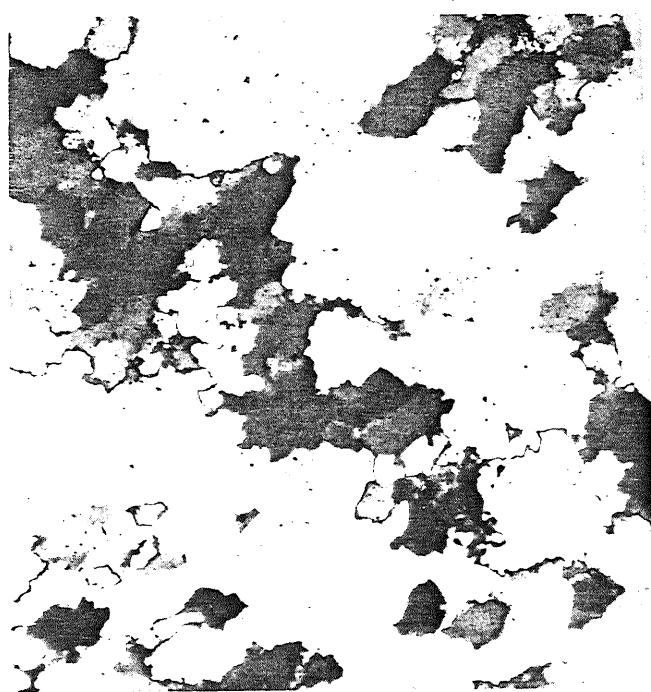


PLATE 11.

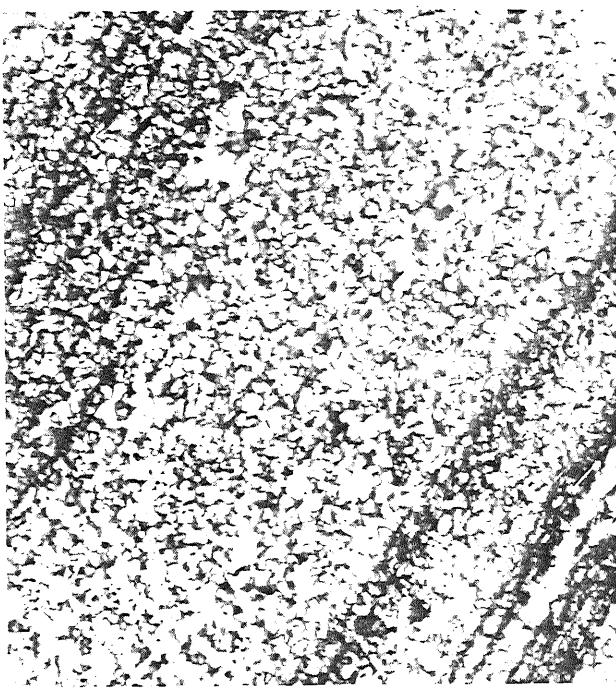


PLATE 12.

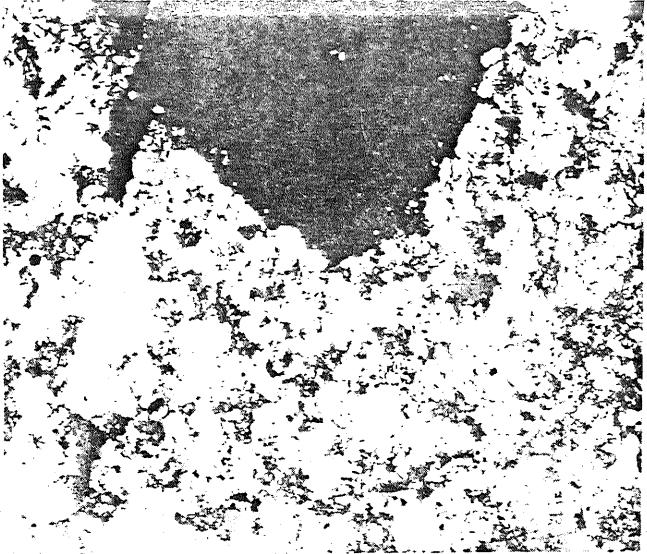


PLATE 13.

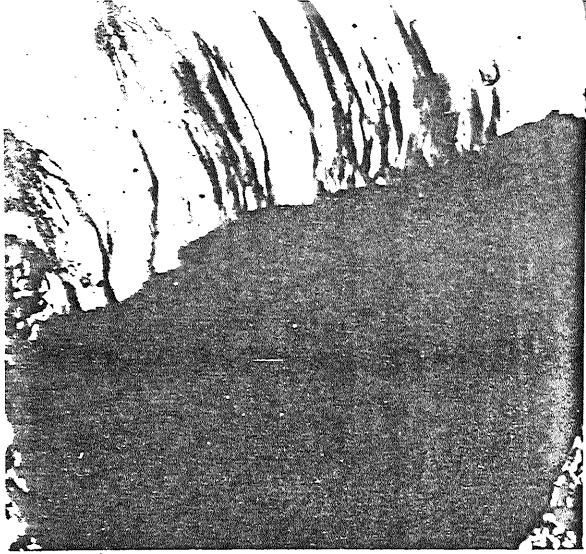


PLATE 14.



PLATE 15.



PLATE 16.



PLATE 17.

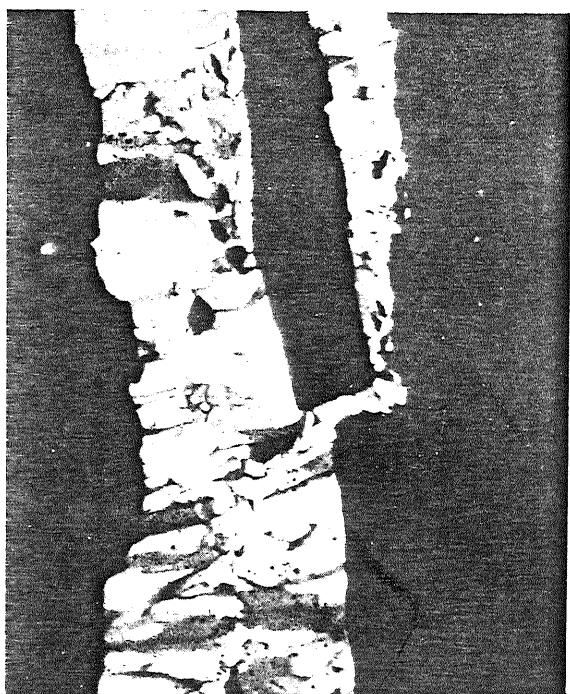


PLATE 18.



PLATE 19.



PLATE 20.



PLATE 21.



PLATE 22.

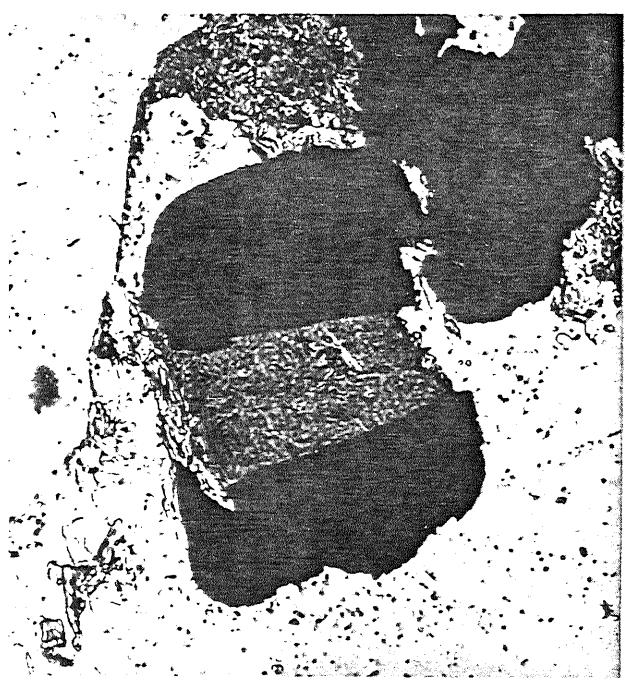


PLATE 23.

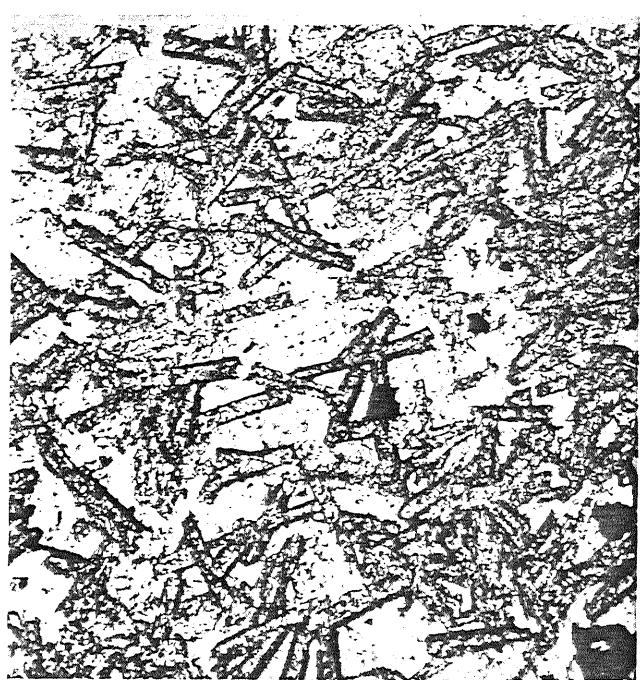


PLATE 24.

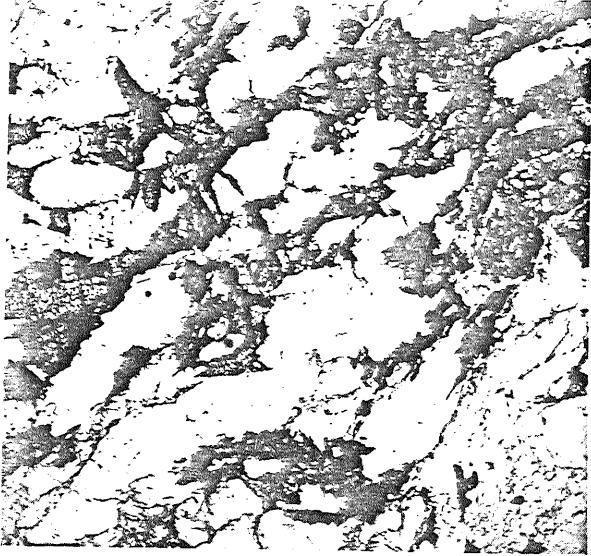


PLATE 25.



PLATE 26.

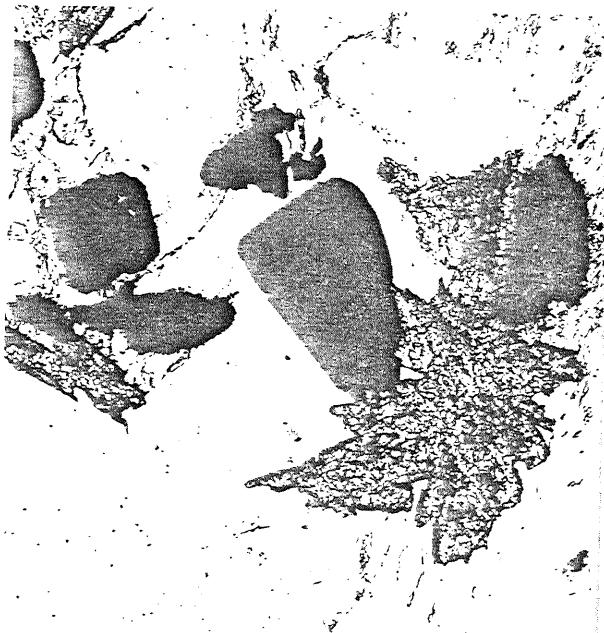


PLATE 27.



PLATE 28.

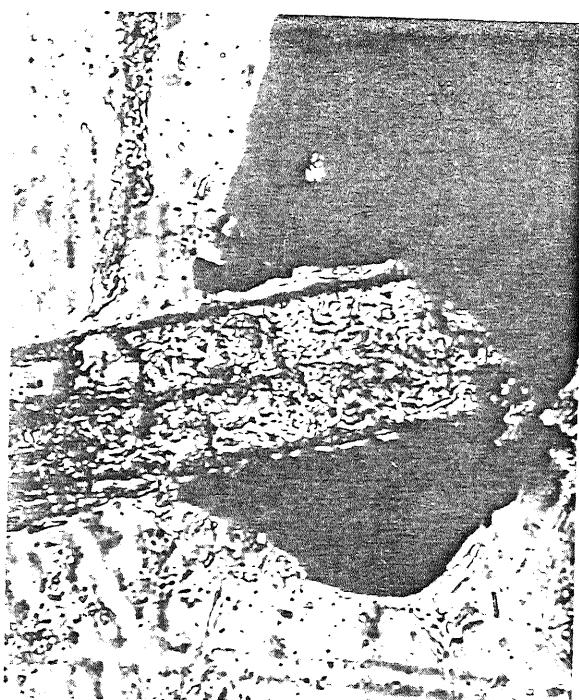


PLATE 29.

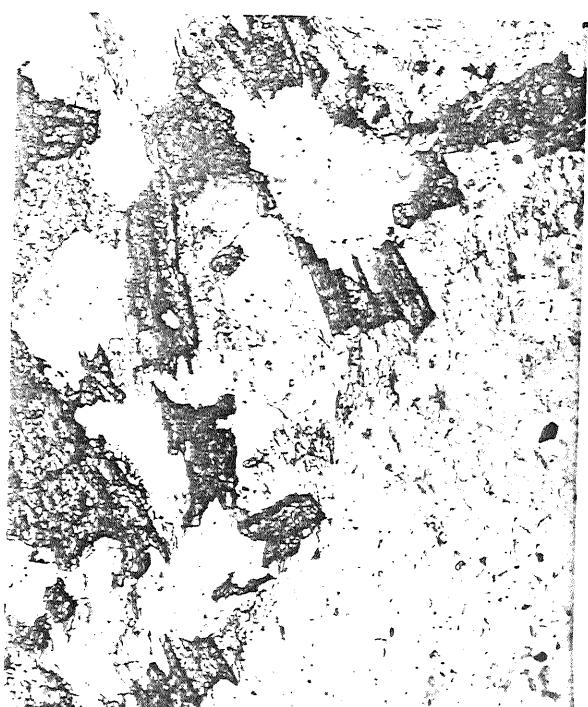


PLATE 30.



PLATE 31.



PLATE 32.

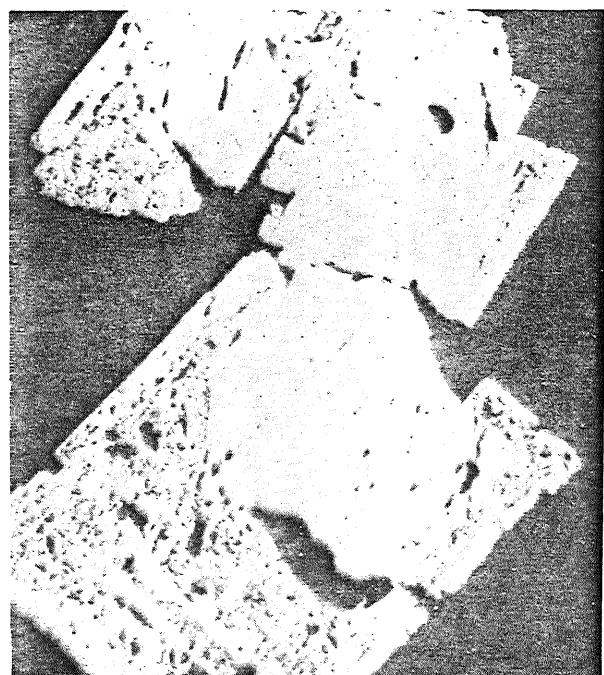


PLATE 33.

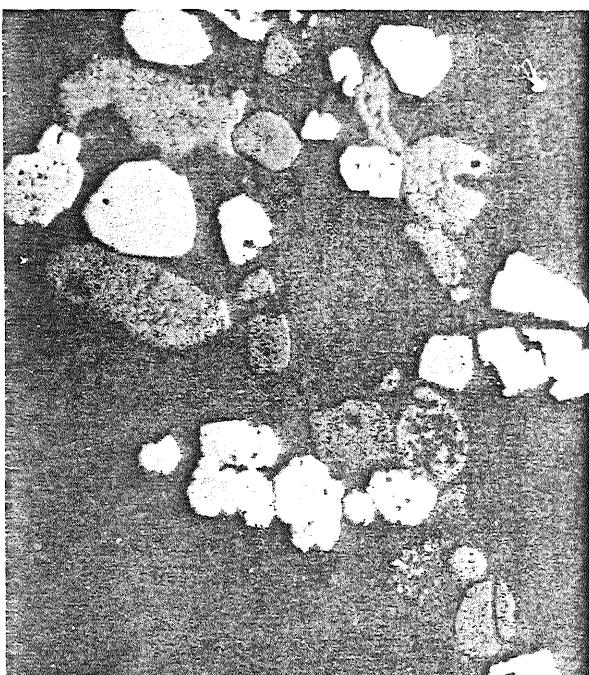


PLATE 34.

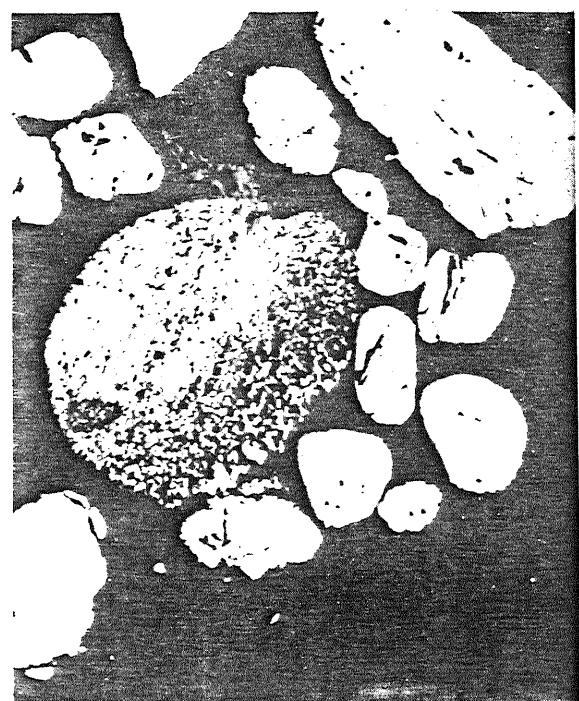


PLATE 35.



PLATE 36.

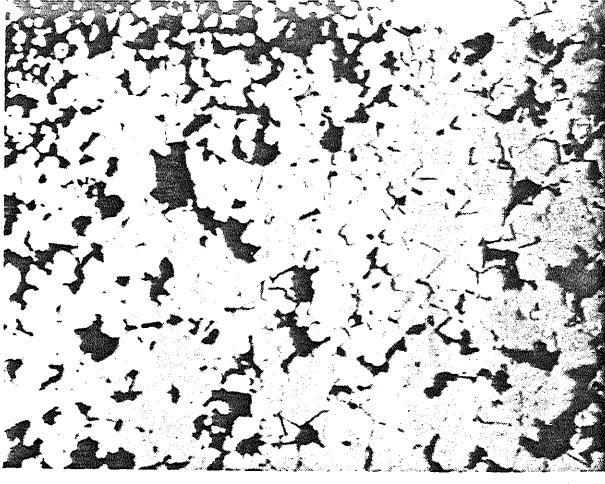


PLATE 37.

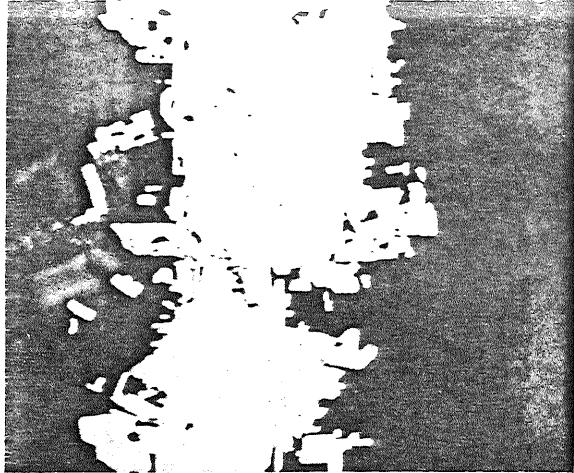


PLATE 38.

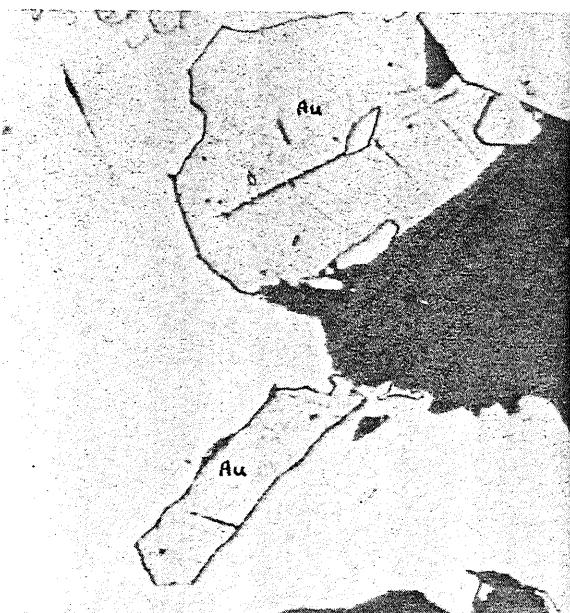


PLATE 39.

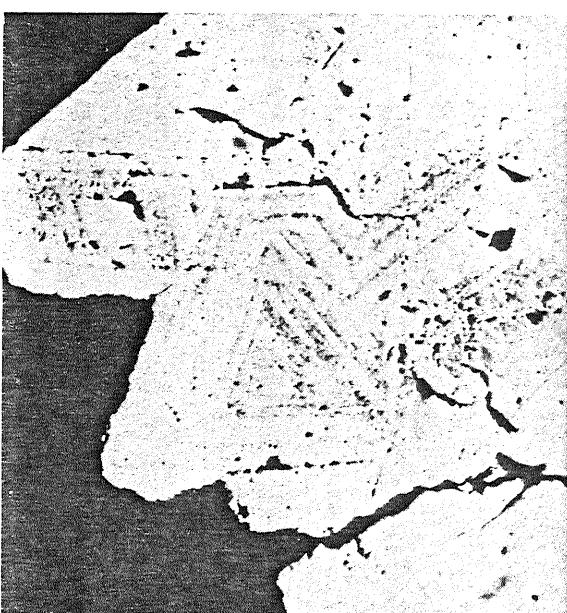


PLATE 40.



PLATE 41.



PLATE 42.

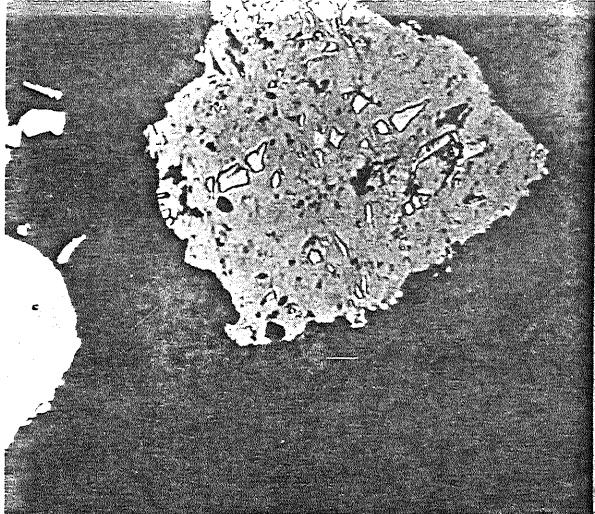


PLATE 43.



PLATE 44.

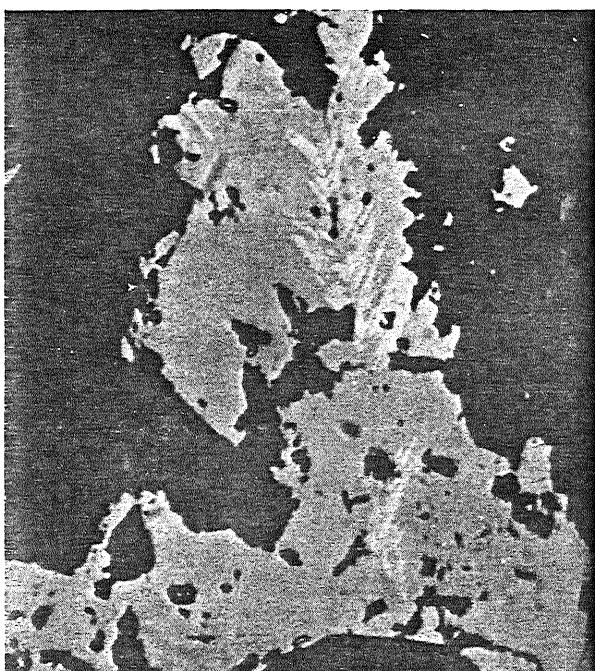


PLATE 45.

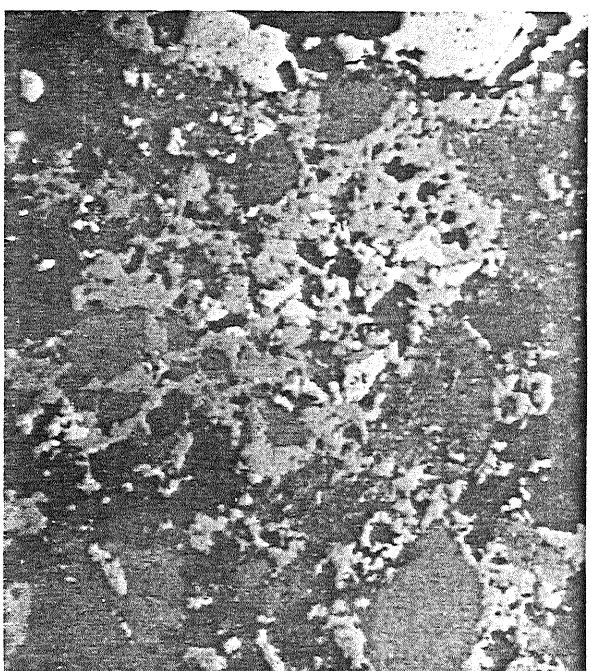


PLATE 46.



PLATE 47.



PLATE 48.

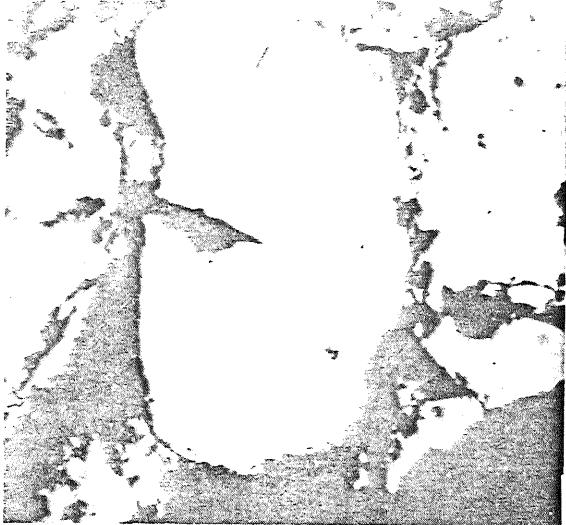


PLATE 49.

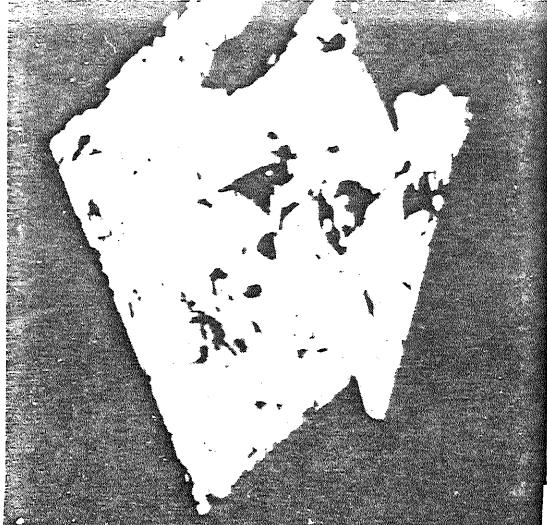


PLATE 50.



PLATE 51.



PLATE 52.



PLATE 53.



PLATE 54.

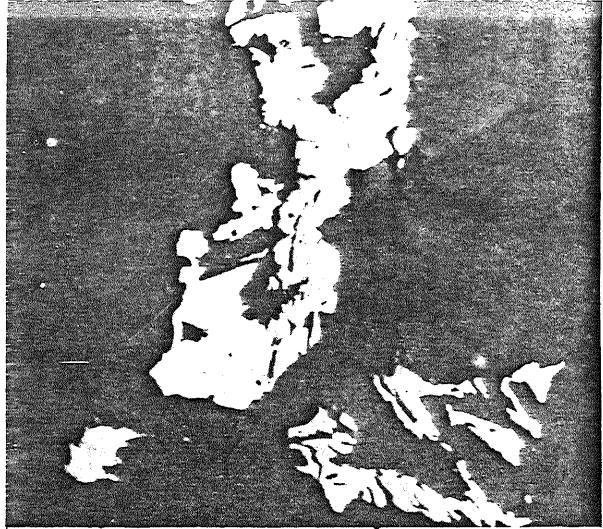


PLATE 55.

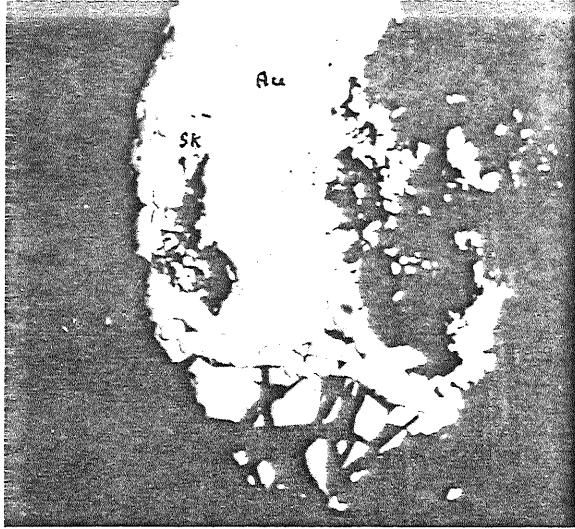


PLATE 56.

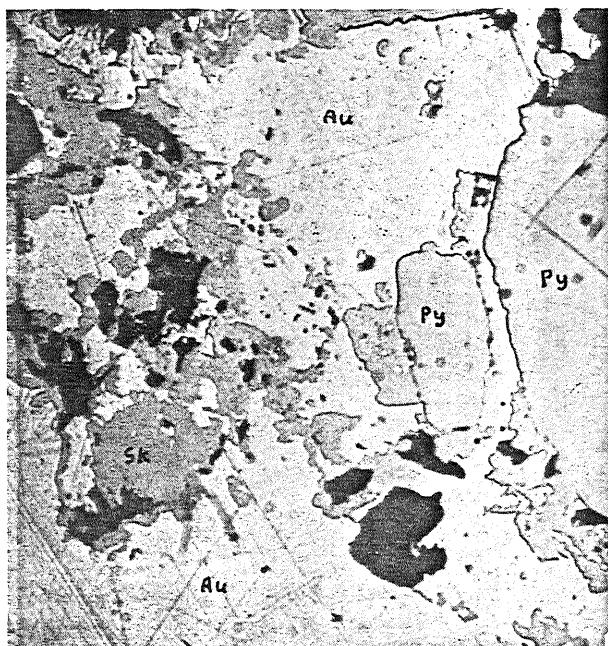


PLATE 57.

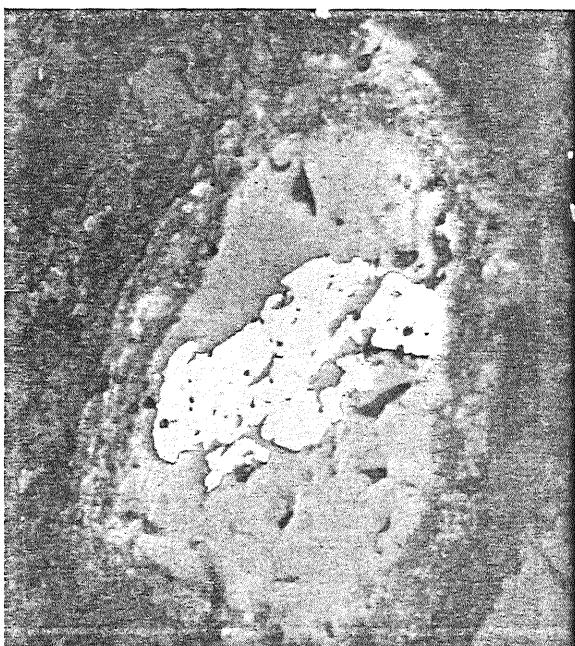


PLATE 58.



PLATE 59.

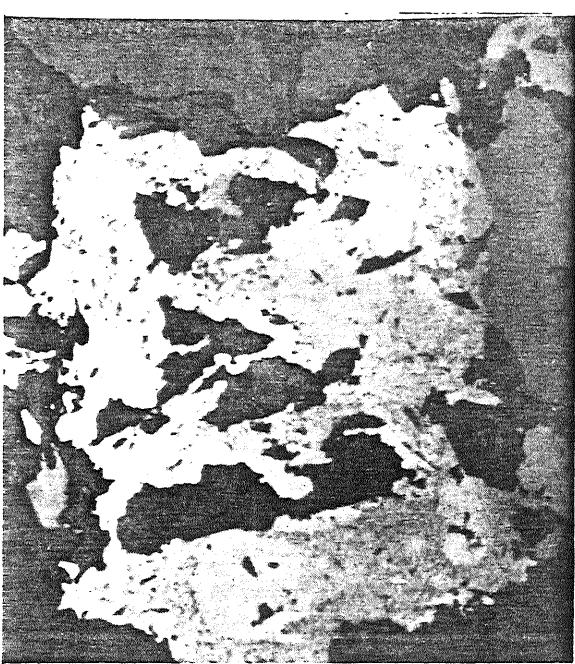


PLATE 60.