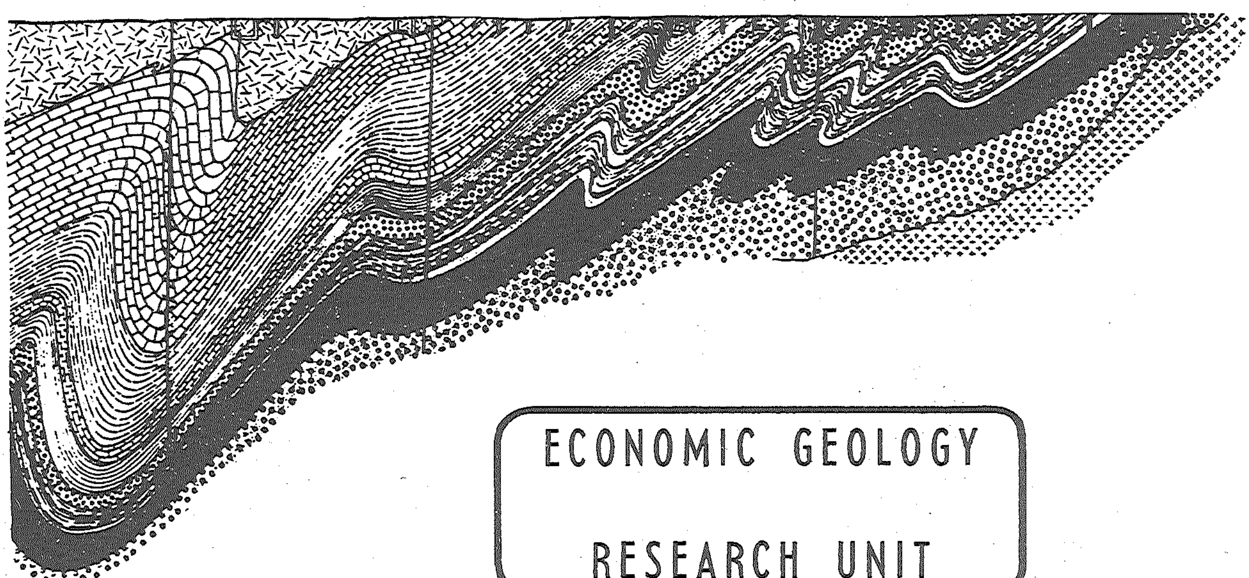
UNIVERSITY OF THE WITWATERSRAND

JOHANNESBURG



ECONOMIC GEOLOGY

RESEARCH UNIT

INFORMATION CIRCULAR No. 41

THE QUANTITATIVE MINERALOGICAL PROPERTIES OF THE MAIN REEF AND MAIN REEF LEADER OF THE WITWATERSRAND SYSTEM

R. P. VILJOEN

UNIVERSITY OF THE WITWATERSRAND

JOHANNESBURG

THE QUANTITATIVE MINERALOGICAL PROPERTIES OF THE MAIN REEF AND MAIN REEF LEADER OF THE WITWATERSRAND SYSTEM

by

R. P. VILJOEN

(Research Geologist)

ECONOMIC GEOLOGY RESEARCH UNIT

INFORMATION CIRCULAR No. 41

January, 1968

THE QUANTITATIVE MINERALOGICAL PROPERTIES OF THE MAIN REEF AND MAIN REEF LEADER OF THE WITWATERSRAND SYSTEM

ABSTRACT

Techniques for the study of indurated sediments from a quantitative point of view have been discussed, as well as the theoretical implications of quantitative data.

The relative percentages of matrix constituents were calculated from the results of a point-count analysis, using a graticule eye-piece. It was found that the relative percentages of the phyllosilicates — chlorite, chloritoid, and sericite (plus muscovite and pyrophyllite) — are of importance. Chloritoid is not present in the Main Reef Leader of the East Rand, but is present to a variable extent in all samples of the Main Reef Leader (Central Rand) and the Main Reef examined. There appears to be an antipathetic relationship between chlorite and chloritoid in the last-mentioned reef. The ore mineralogy of the Main Reef Leader of the East Rand and of the Main Reef Leader of the Central Rand are similar, but it seems unlikely, in view of the uncertain origin of some of the minerals, that the percentage composition of the ore minerals can be used as a basis of comparison of reef horizons. The relative percentages of the three most important heavy mineral constituents — zircon, chromite, and leucoxene — are fairly similar in all three reefs studied. Variations in these percentages are attributed either to different sources of reef material (in the case of the Main Reef), or to selective sorting and alteration of certain components (in the case of the Main Reef Leader of the East and Central Rand).

No large variations in the roundness or sphericity of mineral components were noted, but there appears to be a slight decrease in the length to breadth ratio of zircon grains away from an assumed point of entry of reef material in the East Rand Basin.

Calculations of the median grain-sizes of heavy mineral and quartz distributions of the matrix were made from cumulative curves. The general patterns that emerge are of systematic grain-size decrease in a radial form away from specific points. Sorting values of the heavy mineral and quartz distributions indicate moderate to good sorting, according to both the conventional method and the inclusive graphic standard deviation method. This type of sorting value suggests that the conglomerates were laid down in a fluviatile to beach environment. The lack of marked positive or negative skewness of the various distributions indicates deposition under shallow water marine conditions.

The conspicuous parallelism of the cumulative curves, as well as the consistency of hydraulic ratios, indicate that zircon, chromite, leucoxene, pyrite, and arsenopyrite are in hydraulic equilibrium with each other, and were probably deposited together as detrital minerals. Hydraulic equivalent numbers obtained for pyrite and leucoxene distributions indicate that, in the case of the former, the original mineral was, in fact, pyrite, and not a black sand constituent. In the case of leucoxene, it is probable that the original mineral was sphene, with lesser amounts of ilmenite.

It is believed that the reefs under investigation are not continuous sheets of conglomerates, as was previously thought. Depositional depressions acted as traps for reef material, and were probably joined across structural elevations by poorly-developed conglomerates. Each depression was fed by one or more rivers which debouched into the trap at a confined entry point. This resulted in the reef in each depression having its own characteristics. An unknown degree of mixing of material probably took place

over the elevations, to form the previously assumed continuous conglomerate sheets. Large mineral constituents, as well as generally high gold values, are often associated with the points of entry, where the conditions of deposition were mainly fluvial. Further away from the entry point, with a decrease in mineral size there is a corresponding general decrease in the tenor of gold, and conditions of deposition were probably mixed fluvial and beach, with fluvial conditions predominating.

* *

THE QUANTITATIVE MINERALOGICAL PROPERTIES OF THE MAIN REEF AND MAIN REEF LEADER OF THE WITWATERSRAND SYSTEM

CONTENTS

CONTENTS (Continued)

* *

THE QUANTITATIVE MINERALOGICAL PROPERTIES OF THE MAIN REEF AND MAIN REEF LEADER OF THE WITWATERSRAND SYSTEM

INTRODUCTION

A. THE CONGLOMERATE HORIZONS INVESTIGATED

In this investigation, the quantitative 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. Features such as the relative percentages of heavy mineral constituents and matrix materials have been calculated. Parameters such as mineral size and degree of sorting of mineral distributions have been calculated, and the results obtained plotted on maps and contoured. In addition, some emphasis has been placed on the origin of certain mineral species from the evidence of hydraulic equivalent ratios.

The reefs studied 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, consistently economic conglomerate band, 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, with high, but 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 dies 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 standardize 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. 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 banket 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 represent reef constituting a total strike length of approximately 120 miles from the Doornfontein Mine in the west, to the Witwatersrand Nigel Mine, at the southeast extremity of the East Rand, in the east (see Figure 1). The east-west extent of this area is about 80 miles. Sample localities, as well as the names of mines situated along strike, are given in Figure 1. The localities of five samples of South Reef are also given. The key to the names of the mines is as follows :

	Mine	Abbreviation
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.	Vogelstruisbult Gold Mining Areas Ltd.	Vogelstruisbult
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 quantitative study of the conglomerates was undertaken to determine, if possible :

(i) whether variations in the mineralogy of a particular reef horizon provide evidence as to the mode of deposition of individual conglomerates;

(ii) the processes which were responsible for the 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 a depositional basin;

(iv) whether the Main Reef Leader (East Rand) was derived from a source different to that of the Main Reef Leader (Central Rand);

(v) whether the Main Reef, Main Reef Leader, or South Reef of the Central Rand can be correlated with the Main Reef Leader of the East Rand;

(vi) whether, from mineralogical and petrological data, predictions can be made as to the ultimate extent of known reef horizons, and whether this data can be used in suggesting areas of previously unsuspected payable conglomerates;

(vii) whether mineralogical studies of a particular reef support sedimentological observations in the field;

(viii) whether any mineralogical features can be used to decipher the origin of some of the more problematic minerals within the banket.

C. BRIEF REVIEW OF PREVIOUS 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 covering the mineralogy of all the reefs. The detailed mineralogy of a particular reef on a particular mine is frequently well-known, but very little has been done to determine the systematic variations in the mineralogy of the same reef on a regional scale.

Valuable quantitative data were gathered by Reinecke (1927), who mentioned factors probably responsible for the concentration of gold, and by Pirow (1920) who studied the distribution of pebbles. More recently, Whiteside (1944) used the ratio of heavy minerals as an aid to correlation, and Fuller (1958) described the petrology of the banket, as a whole, from a quantitative point of view. Koen (1961) carried out a size analysis on the uraninite, zircon, and chromite fractions of several samples of Witwatersrand banket, and investigated the possibility of hydraulic equilibrium existing between these minerals.

D. ACKNOWLEDGEMENTS

Appreciation is expressed to the following mining groups which supplied all the samples used in the present investigation :

Anglo American Corporation of South Africa, Ltd.
Gold Fields of South Africa, Ltd.
General Mining and Finance Corporation, Ltd.
Johannesburg Consolidated Investment Co. Ltd.
Rand Mines, Ltd.
Union Corporation, Ltd.

Thanks are due to the management and geological staffs of the following mines which supplied the samples :

Spaarwater	E.R.P.M.
Sub-Nigel	Rose Deep
Vlakfontein	City Deep
Vogelstruisbult	Crown Mines
Marievale	C.M.R.
East Daggafontein	Durban Deep
Daggafontein	Luipaardsvlei
S.A. Lands	West Rand Cons.
Van Dyk	Venterspost
Geduld	Libanon
East Geduld	West Driefontein
Grootvlei	Doornfontein
Modder East	

The writer is indebted to Dr. W. J. Liebenberg and Dr. S. A. Hiemstra of the National Institute for Metallurgy, Johannesburg, and to Dr. G. M. Koen of the Anglo American Central Metallurgical Laboratory, for guidance during the early stages of the investigation.

Financial assistance for the undertaking of the project was received from the C.S.I.R.

THE NATURE OF THE INVESTIGATIONS AND THE METHODS OF STUDY

In the study of indurated sediments, such as those of the Witwatersrand System, it is difficult to separate the rock into component mineral grains by normal crushing procedures. An examination of thin-sections and polished-sections reveals that many of the heavy mineral grains, especially the larger individuals, are severely fractured in situ. Crushing of the rock would produce many fractured individuals which, if measured in an endeavour to obtain quantitative data concerning parameters such as size, would lead to spurious results. It is for this reason that the entire investigation was carried out with the aid of sections, i.e. thin-sections, polished-sections, and polished-slabs. All percentages concerning mineral frequencies and volumes have been obtained from data gathered from the study of such sections.

A. PERCENTAGE COMPOSITION OF MATRIX MATERIAL

In the study of the matrix material, allogenic grains with a diameter, or maximum horizontal intercept, of 2 mm. or less were considered. All the phyllosilicates were included, but no counts of heavy mineral constituents, which normally constitute about 1% or less of the total matrix, were made. Sulphides were not included because of their general erratic manner of distribution and doubtful origin.

Much has been written about the correct procedure of sampling sedimentary rocks. In this study the choice of a method was influenced by the type of samples available and the aims of the investigation. Where four or five samples were available over 10 to 100 feet along the reef horizon, one thin-section was cut from every sample. Where only one sample was available from a particular area, an endeavour was made to cut two or more thin-sections. Where possible, sections were cut from areas of reef relatively low in sulphide, and care was taken not to include intercalated quartzitic lenses, or portions of reef with unusual characteristics. The mode of each sample was calculated and totalled for one, or a number of, thin-sections, depending on the type of sample, to give a volumetric appraisal of the matrix material present in a particular locality. The minerals included in the modal analyses were allogenic quartz (sand and silt); sericite, muscovite, and pyrophyllite, grouped together; chlorite and chloritoid. In essence, the method of computation was similar to that described by Chayes (1949), whereby the sample is divided up into a number of small blocks by a superimposed grid, either of the point-counter-type or the graticule-eye-piece-type. To avoid counting small pebbles and granules, a graticule eye-piece was used instead of a point counter. The portion of the matrix under investigation was covered by a bilaterally symmetrical grid of points .25 mm. apart. Examination was made under low-power magnification to give a more general appraisal of the composition of the matrix. Calculations of the modal composition of the matrix of a particular section were based on over 500 points. For every locality, therefore, with an average of three thin-sections per locality, between 1,500 and 2,000 points were used in the calculations of the mode (volume per cent) of the matrix.

From the data obtained in the above-mentioned manner, the following were determined (represented in Table 1) :

(i) the relative percentages of the various phyllosilicates occurring within the matrix, i.e. sericite (plus muscovite and pyrophyllite), chlorite, and chloritoid;

(ii) the relative percentages of quartz (sand plus silt), sericite, and ferromagnesian minerals (chlorite and chloritoid); and

(iii) the relative percentages of quartz (sand), quartz (silt), and total phyllosilicates.

From these results, triangular plots were made where noticeable differences existed between reef horizons, or within particular horizons.

B. PERCENTAGE COMPOSITION OF ORE MINERALS

In this study, all the sulphides present, plus gold, uranium, and carbon, were included.

A number of factors influenced the choice of a suitable area for the taking of samples to be prepared for polished-sections. Where possible, samples were taken from portions of reef relatively rich in sulphide, care being exercised not to include portions greatly enriched by secondary sulphide, such as chalcopyrite. It was usually found that the relative proportions of the ore minerals in areas fairly rich in sulphide agreed tolerably well with the relative proportions of the ore minerals in areas of the same sample fairly poor in sulphide mineralization. At least one polished-section was cut from every sample available, and, in cases where 4 or 5 samples were present in 10 to 100 feet of reef, up to 6 polished-sections were made. In such instances, the averages for the ore minerals present in each of the polished-sections were calculated. The percentages were determined by means of a Swift automatic point-counter, tabulated in such a way that each movement in a horizontal direction was equal to .16 mm. Vertical traverse spacings (i.e. along north-south traverses) were set at .33 mm. intervals. About 500 to 700 points were counted, on an average, for each polished-section, and results were based on this count. Gangue material, mainly quartz and phyllosilicates, was not taken into account.

From the results obtained, a table indicating the relative percentages of ore minerals in the samples studied was drawn up (see Table 2). It should be stressed that the percentages obtained in this manner are accurate for a particular polished-section, but it is likely that numerous polished-sections would be required to ensure confidence that the percentages obtained are representative of a particular portion of reef covering up to, say, 100 feet. It is known, for example, that the pyrrhotite content of a particular conglomerate horizon may vary by as much as 80% or more over a distance of a few feet. Large variations in the carbon content of the conglomerates studied were also noted. It is for these reasons that the figures presented are intended only to show broad trends in the ore mineralogy.

C. PERCENTAGE COMPOSITION OF HEAVY MINERALS

During the course of the investigation, counts were made of heavy mineral constituents, with a view to determining the relative percentages of the dominant and most persistent groups, i.e. zircon, chromite, and leucoxene. It was anticipated that the relative percentages of these minerals in a particular sample would remain fairly constant, irrespective of the total volume of heavy minerals present.

In an endeavour to minimize possible discrepancies, samples were taken from the top, middle, and bottom (often characterised by an accumulation of heavy minerals) of reef bands, where possible, and over about 10 to 100 feet of reef, where suitable material was available. Initially, counts were made of rounded carbon nodules, in most cases undoubtedly representing replacement of original uraninite grains (Liebenberg, 1955), but results obtained by including carbon appeared spurious, and this was discontinued. Uraninite and other heavy mineral particles, such as tourmaline, apatite, and osmiridium, were not included because of their rarity of occurrence, and the erratic distribution, especially of uraninite.

The following tabulation shows the results obtained in a particular test sample over 10 feet of reef : (i) including all constituents counted, and (ii) including the relative percentages of zircon, chromite, and leucoxene grains only. The consistency of the relative percentages of zircon, chromite, and leucoxene is apparent.

Relative Percentages of Heavy Minerals

(i) All constituents counted

Sample	Zircon	Chromite	Leucoxene	Uraninite	Carbon	Others
Crown Mines 8a	25.40	2.60	70.03	.97	.32	.60
Crown Mines 8b	25.42	3.38	69.49	-	-	1.69
Crown Mines 8c	19.49	3.14	42.13	1.88	32.07	1.25
Crown Mines 8d	22.56	4.26	68.29	.60	3.04	1.21
Crown Mines 8e	27.94	5.67	61.13	1.31	3.93	1.23

(ii) Zircon, chromite, and leucoxene only

Crown Mines 8a	25.91	2.65	71.43
Crown Mines 8b	25.86	3.43	70.69
Crown Mines 8c	30.09	4.84	64.76
Crown Mines 8d	23.71	4.47	71.80
Crown Mines 8e	29.49	5.98	64.52

It is well known that particular sedimentary horizons are often characterized by a particular suite of heavy minerals which usually remain constant, as far as relative proportions are concerned, over fairly large areas. It has been established that characteristic heavy mineral assemblages are particularly useful for purposes of correlation, and, as a result, they have been widely used in oil geology. Some investigators have used the presence or absence of one or more diagnostic minerals as a criteria for comparison. The most common method, which is the method adopted in the present investigation, is to compare number frequencies directly as percentages, providing a similar number of grains have been counted in all samples. Other investigators, e.g. Pettijohn (1957), have made one mineral, such as garnet, a base to which relative proportions of other minerals are compared. In the present investigation, it was found inconvenient to use one mineral as a basis for comparison. Zircon and chromite would appear to be suitable, but in the samples studied they occur in relatively minor amounts. Leucoxene, because of its probable diverse origin and extent of alteration, is unsuitable.

The problem as to how many grains should be counted for the percentages to be statistically accurate has been dealt with by Dryden (1931). The question is basically one of sampling error, and according to the law of diminishing returns, 300 grains counted will suffice for ordinary work. In the present investigation, an average of about 450 grains per sample were counted. Misleading conclusions concerning the relative importance of various sources may be drawn, if the weight of heavy minerals is not considered (Rittenhouse, 1943). If percentages are identical, however, there is no question regarding the statistical similarities of the samples, although, as pointed out by Dryden (1931), geological formations of different age or history might have identical, or very similar, mineral frequencies.

Differences in the relative percentages of heavy minerals from one source area to another may vary considerably when the same quantities of host-rock are being eroded at the same time. Fairly abrupt differences are often caused by contamination with the heavy mineral content of underlying bedrock or strata, and marked changes in heavy mineral content have been used in places to show the existence of unconformities. Away from the source, with constant reworking, both the total amount of heavy minerals and the number of mineral species are likely to diminish. The proportion of zircon (due to its resistance to both chemical attack and abrasion) is likely to increase relative to other heavy minerals. On the Witwatersrand, Whiteside (1944) has used the relative proportions of zircon, iron ores (mainly chromite), and leucoxene, in an attempt to find a useful method of correlating reef horizons. Heavy minerals for the above study were obtained by crushing samples of banket from the Kimberley (May) and Main Reef Leader horizons of the East Rand.

All results pertaining to the relative percentages of heavy minerals were plotted on three-component and two-component scatter diagrams.

D. SHAPE OF MINERAL PARTICLES

So many geological factors are involved in the development of shape that any criterion of origin, based on a single principle, is likely to be unreliable.

No special study of the sphericity of mineral particles was carried out, although Smithson (1939) has reported a downcurrent increase in the sphericity of minerals such as zircon. His studies were based on the ratio of the long axis to the short axis of zircon particles. A number of such measurements were made during the present investigation. No systematic examination of the roundness of mineral particles was carried out, except in so far as to give a general description of this property. Not much data are available on the rate of rounding of mineral grains within the sand-grade. It would appear that the process is a very slow one, and in some cases does not even apply. Russel and Taylor (1937) have shown that the roundness of quartz particles actually decreases in a downstream direction in the Mississippi River. The increased degree of angularity is attributed mainly to fracturing.

The effect of rounding by transporting media on pebbles is much greater than in the case of sand-grade particles. Two major difficulties, however, arose in the measuring of pebble roundness in the present investigation: (i) the roundness had to be computed from sections, and (ii) most samples available contained insufficient pebbles for reliable statistical computations. According to Krumbein (1941), at least 25 pebbles are necessary, and preferably 50. For these reasons, no special study of pebble roundness or sphericity was made.

E. SIZE OF MINERAL PARTICLES

(a) Methods of Measurement

For rapid work, the size of a particular mineral grain in section may be expressed as the maximum horizontal intercept, or longest diameter, across the grain (Krumbein, 1953). This definition of grain-size has been adopted for the present investigation. A number of drawbacks are immediately apparent, however, in expressing grain-size as measured in section. The size obtained will not be an accurate measure of the true size, and, in general, it may be said that the size of particles measured in section will be less than the grain size of loose particles. Krumbein (1953) has shown that, in the case of spherical particles, there is a definite relationship, so that mathematical analysis may determine what corrections must be applied to the random sections to convert observed size into true size. The average radius of a sphere computed from sectional analysis is .763, or about 76%, of the true radius. The technique of measuring the size distribution of mineral particles in section has also been investigated by Greenman (1951), Rosenfeld et al (1953), and Packham (1955), the last-named author having developed a useful graphical solution to the problem of relating sectional size to true grain-size. For the purposes of the present investigation, conversion of observed sectional diameters to true diameters, or size, was unnecessary. All that was required were the relative sizes of heavy minerals, to facilitate comparisons, and to determine the relative increase or decrease in grain-size from one locality to another. As most of the mineral particles measured were roughly spherical in shape, a rough approximation of the true grain-size could be computed from the data obtained by applying a constant factor.

The method of size measurement adopted was similar to that used by Koen (1961). A number of rock slices were cut from each sample, given a rough polish, and covered with a thin layer of micro-oil. A sufficient number of slices (usually 4 to 5, but sometimes as many as 10) were used to satisfy statistical requirements. All mineral constituents were measured in section with the aid of a micrometer eye-piece. Regular north-south traverses were made across thin-sections, polished-sections, and polished-slabs. Use was made of a mechanical stage, care being taken to cover the entire section under examination by slight overlap of individual traverses. Where possible an attempt was made to measure at least 200 grains of each particular mineral species. In some cases, however, the heavy minerals were very sparsely distributed, and only 100 grains of each variety were measured. It appeared as though 50 grains were sufficient, in most cases, to give a fairly good appraisal of the size frequency distribution of a particular mineral species, provided the median grain sizes only were considered. On the average, 150 grains of a particular mineral were measured from every sample.

(b) Precautions Observed in Size Measurement

In the case of pyrite, only grains displaying perfectly preserved rounded edges, with a spherical to oval shape, were measured. Many individuals, although displaying an original rounded outline, have undergone recrystallization, or have been surrounded by later, secondary, compact pyrite. These pyrite grains, although roughly spherical, have an irregular outline, and were omitted from the size analysis. In some cases, where the surrounding pyrite is of the porous crystalline variety, the original rounded grain boundary is clearly visible. Such grains were included in the size analysis. Care was taken not to measure large rounded grains of pyrite which could originally have been of the porous variety and could have been compacted subsequently. In the case of rounded particles of arsenopyrite, glaucodot, and cobaltite, the same procedure as outlined above for the measurement of pyrite was adhered to. In general, the growth of secondary material around these minerals is negligible, and, the original grain outline is often clearly discernible.

Measurement of zircon grains in polished-slabs was facilitated by the distinctive pinkish colour of the mineral. Care was taken to measure only the obviously rounded grains. Angular fragments were ignored, as these probably originated from detrital rounded grains, and fractured prior to, or just after, deposition. Zircon inclusions within quartz pebbles were not measured. Chromite particles were treated in much the same way as the zircon grains. In places, recognition of grain boundaries under Ultrapak illumination, was made difficult by the mineral being surrounded by dark chloritic matrix material. In such instances measurements were not carried out. Leucoxene grains were, in many cases, very difficult to measure, because of the remobilized and altered state of the material. Only grains showing positive signs of a definite core (i.e. not completely leucoxenic), and with a well-defined spherical or oval shape were measured. Despite the care that was exercised in the size measurement of leucoxene grains, the results obtained are not as reliable as the results obtained from the measurement of primary constituents such as chromite and zircon. Measurement of quartz grains in the sand range was straightforward, where original outlines were preserved. In the majority of cases, however, the extensive development of authigenic quartz, and the replacement of grain edges by small flakes of sericite, masked the original size and shape. As a result, interpolation of size had to be made in a number of instances. Observed size distributions of the quartz fraction are, therefore, in common with the size of leucoxene distributions, not as reliable as those of the heavy minerals zircon and chromite.

Great care was taken in the measurement of fractured grains generally. Where fracturing was so severe that individual components had moved away, and were disorientated with respect to each other, measurement was not carried out. In the majority of cases, however, where fracturing or replacement of a particular grain had taken place, the original size of the particle could be deduced by interpolation.

(c) Methods of Representing Size Data

After the size values of the different heavy mineral fractions studied have been converted into millimeters, division into a number of size classes, or grades, as is common in any statistical study, is necessary. Such a subdivision of particle sizes into an essentially continuous scale is made to standardize terms, and to create sufficient classes to facilitate statistical analysis. A purely linear (or arithmetic) scale with millimeter graduations is unacceptable, and such linear scales can seldom be used for naturally occurring substances. This is because the range of sizes to be subdivided is usually very great, and a true portrayal of grain-size distribution would only be obtained if an impractical number of grades were used. Scales used for any naturally occurring material must therefore be logarithmic. Koen (1961) has described the essential difference between arithmetic and logarithmic scales. Udden (1898), quoted by Pettijohn (1957), realized the need for a logarithmic scale for the statistical analysis of clastic particles, and proposed what is now known as the Udden Scale. This scale has been widely used since. Udden chose one millimeter as the starting point of his scale, and used the ratio of $\frac{1}{2}$ for material smaller than one millimeter, and the ratio of 2 for material larger than one millimeter, and thus obtained the diameter limits of 1, 1/2, 1/4 and so forth, and 1, 2, 4, 8 and so on, in the other direction, for his size class limits. The scale is, however, not suited to the analysis of well-sorted sediments, such as those of the conglomerates investigated, because the class intervals are too far apart. For this reason the Udden $\sqrt{2}$ Scale, which is a modified Udden Scale in that each Udden class is divided into two sub-classes, has been proposed. The Udden $\sqrt{2}$ Scale has been used in the present investigation. The scale has the disadvantage, however, of giving rise to irrational numbers and irrational statistical parameters because of its logarithmic nature. In order to avoid these irrational numbers, and to facilitate simplified statistical computations, the Phi (ϕ) Scale was proposed by Krumbein (1934). This scale proposes that the class limits of the unmodified Udden Scale be expressed as powers of two. The logarithm of the class limits to the base 2 is used, and, to avoid negative numbers for material less than 1 mm. in diameter, the log is multiplied by - 1, or

$$\text{Phi} = -\log_2 \times \text{Udden Scale class limit (mm.)}$$

The following table shows the relationship between the Udden Scale, the Udden $\sqrt{2}$ Scale, and the Phi (ϕ) Scale. All these scales have the same general class limits.

Udden Scale	Udden $\sqrt{2}$ Scale	Phi (ϕ) Scale
16.00 - 8.00 mm.	16.00 - 11.31 mm.	- 4
	11.31 - 8.00 "	
8.00 - 4.00 "	8.00 - 5.75 "	- 3
	5.75 - 4.00 "	
4.00 - 2.00 "	4.00 - 2.83 "	- 2
	2.83 - 2.00 "	
2.00 - 1.00 "	2.00 - 1.414 "	- 1
	1.414 - 1.00 "	
1.00 - .50 "	1.00 - .707 "	0
	.707 - .500 "	
.50 - .250 "	.500 - .354 "	1
	.354 - .250 "	
.25 - .125 "	.250 - .177 "	2
	.177 - .125 "	
.125 - .062 "	.125 - .088 "	3
	.088 - .062 "	
.062 - .044 "	.062 - .044 "	4

The size frequency distribution of any sediment is continuous, and can be represented by a curve. Such a curve is not attainable, however, unless all the constituent grains within a particular sediment are measured. Histograms are the easiest devices for representing the size distribution of a particular mineral component, if all the grains have not been measured. Histograms were used in the present study for representing the size distribution of quartz grains within the matrix only. In view of the fact that the quantitative data obtainable from histograms are limited, cumulative curves were used for depicting grain-size distributions for most of the mineral components. These curves are constructed by plotting the cumulated percentages of each class against size in millimeters, using the Udden $\sqrt{2}$ Scale, which is logarithmic. The following table shows an example of the layout adopted for the mechanical analysis of mineral components, and some constructed curves are shown in Figures 15 and 16. In the present investigation, percentage in a particular class refers to percentage by number or count, and, although related, is quite different to percentage by weight obtained by sieve analysis (Pettijohn, 1957).

Marievale (Mechanical Analysis of Zircon)

Size Grades (mm.) Udden $\sqrt{2}$ Scale	No. of Grains Measured	Percentage	Cumulative Percentage
.031 - .044	2	.78	99.96
.044 - .062	18	7.05	99.18
.062 - .088	26	10.19	92.13
.088 - .125	84	32.94	81.94
.125 - .177	78	30.58	49.00
.177 - .250	33	12.94	18.42
.250 - .354	12	4.70	5.48
.354 - .500	2	.78	.78
.500 - .707	-	-	-
Totals	255	99.96	99.96

Cumulative curves have the advantage over histograms of providing a better approximation of the continuous size distribution of the particles under examination, in addition to revealing small differences in texture between mineral distributions. Thus, for example, the slope of a particular curve is a measure of sorting of a particular sediment. Besides visual comparisons, differences in curve shape and slope can be quantitatively assessed directly from the curve by means of statistical measures. Quartile measures (or measures defining the shape of the curve) are most commonly used, and are of great advantage in that they are easily determined from the constructed cumulative curves. The most important quartile measure is the median, "as the middle-most member of the distribution, is that diameter which is larger than 50% of the diameters in the distribution, and smaller than the other 50%" (Krumbein and Pettijohn, 1938). The median (Md) is not affected by extreme grains on either end of the distribution, and has the advantage of being computable without the complete analysis. The first and third quartiles correspond to frequencies of 75% and 25%, respectively. By convention, Q1, or the smaller diameter, is taken as the first, or 75%, quartile, and Q3, or the larger diameter, as the third, or 25%, quartile. These values can be read directly from the cumulative curve.

From the above parameters of frequency distribution, the following measures can be calculated :

(i) the sorting, or spread of the curve, measured by the coefficient of sorting (So); the sorting coefficient as defined by Trask (1932) is :

$$So = \frac{Q3}{Q1} \quad \text{where } Q3 > Q1$$

(ii) the skewness, or symmetry, of the cumulative curve (Sk), defined as :

$$Sk = \frac{Q1 - Q3}{(Md)^2}$$

The table below is an example of the standard layout for the tabulation of statistical measures read from the cumulative curves constructed.

Zircon (size values in mm.)

Sample	Median Md	Third Qt. Q3	First Qt. Q1	Sorting Coeff. So	Skewness Sk
Geduld	.291	.414	.208	1.41	1.028

The advantages of single-number representation of these properties of size frequency distribution (Md, So, and Sk) permit them to be plotted on a map and contoured, giving direction of current flow and other data. Decrease in grain-size, as measured from the median of the distribution, can be used in determining the entry point of material into a basin of deposition. The exact geological significance of skewness is not clear. Sorting generally gives a good indication of the environment of deposition of a particular sediment. Skewness may decrease downstream, or away, from an entry point of material, as indicated by Plumley (1948).

Sorting is generally regarded as one of the most useful textural attributes of sedimentary rocks. According to Trask (1932), a sorting coefficient value (So) of less than 2.5 indicates a well-sorted sediment, a value of 3.0 normally sorted, and a value greater than 4.5, poorly sorted. These values, as pointed out by Hough (1942), quoted by Pettijohn (1957), are probably too high, and most near-shore marine sediments of the sand-grade have sorting coefficients between 1.0 and 2.0. These numbers do not, however, signify the true spread of the curve, because they are geometric rather than arithmetic. It has recently become apparent that Trask's method for determining sorting, which has been widely used in sedimentary petrography in the past, is unsuitable in many cases, and several investigators have objected to its use on theoretical grounds. The objections have arisen mainly from the fact that only the sorting between the 25% and 75% quartiles is measured. This, in fact, means that the Trask sorting coefficient is a measure of only the central 50% of a particular distribution, and does not take into account the extremities of the curves, which may be diagnostic of changes in the sorting of a particular sediment from different areas (Folk, 1961). As a result, new sorting coefficients, based on larger sections of the distributive curve, have been introduced in recent years. For example, Friedman (1962) quotes Inman (1952) and Folk (1954) as having advocated the use of sorting measures employing the 16th. and 84th. percentiles (i.e. the central 68% of the distribution). The inclusive graphic standard deviation method, which covers 90% of the grain-size distribution, was introduced by Folk (1961). All these methods have, however, practical disadvantages for some types of sediments, and, for this reason, Friedman (1962) suggested a new genetic classification, based on the standard deviation (a moment measure) which has an environmental significance. The standard deviation method, then, is a measure of the spread of the grain-sizes (sorting), and is based on the entire grain population, or 100% of the distributive curve. Friedman (1962) arranged the grain-size distribution in ϕ values, with the mean defined by the equation $\bar{x}\,\phi = \frac{1}{100}\sum fm\,\phi$, where f is the frequency, or abundance, of the different grain-size grades present in the sediment, $m\,\phi$ is the midpoint of each grain-size grade (in ϕ values), and $\bar{x}\,\phi$ is the mean (in ϕ). The standard deviation is defined by the equation

$$\sigma\,\phi = \sqrt{\frac{\Sigma f\,(m\,\phi - x\,\phi)^2}{100}}$$

From the standard deviation the skewness, or third moment, can be calculated. Friedman (1962) stated that "skewness defines the symmetry of the curve and can be described as the tendency of a distribution to depart from a symmetrical form". Skewness is statistically defined as the average of the cube of the standard deviation. It is expressed by the equation

$$a3\phi = \frac{1}{100}\,\sigma\,\phi^{-3}\;\Sigma f\,(m\,\phi - \bar{x}_{\phi})^3$$

A plot of sorting (standard deviation) against skewness is useful for determining the environment of deposition.

Besides the statistical parameters derived therefrom, cumulative curves have the additional advantage (if a logarithmic size-scale is used) of showing whether mineral fractions are in hydraulic equilibrium with each other. In order to understand the concept of hydraulic equilibrium, it is necessary to enquire into the laws which govern the settling of mineral particles through a fluid medium, in this case, water. A pebble, or a particle of sand (quartz), or a heavy mineral component, or a silt particle, when dropped into water, has, for a moment, an accelerating velocity. On account of the resistance of the water, however, the velocity of fall immediately becomes uniform, and the particle continues its fall at a steady rate. This uniform settling velocity reflects Stoke's Law, which is the classic statement of the settling velocity of spherical particles, if standard conditions are assumed. The law holds for small spheres (under .08 mm.), but departures are to be expected from grains over .2 mm. in diameter. Rubey (1933) cited experimental evidence showing that grains more than 1.55 mm. in diameter fall with velocities which vary with the square root, instead of the square, of the velocity. Thus, it can be said that larger particles within the limits of Stoke's Law, with low specific gravities, have the same velocity of fall through a fluid medium as smaller particles, with higher specific gravities. These particles are then said to be in hydraulic equilibrium with each other. Rittenhouse (1943) applied the concept to sedimentary particles, and showed that the size distribution of heavy minerals is, in general, similar to that of quartz, and that the heavy minerals are finer in texture than the light minerals. Increasing specific gravity is accompanied by increasing fineness of the heavy minerals.

If visual examination of the cumulative curves of the heavy minerals (and possibly quartz) in a particular sample indicates a parallel arrangement, then it is likely that the minerals under examination are in hydraulic equilibrium with one another. This property of cumulative curves is particularly useful in helping to determine the genetic significance of the size distribution of some of the more problematic minerals occurring within the banket. For example, Koen (1961) showed that the cumulative curves, illustrating the various uraninite distributions in Witwatersrand banket, have the same shape and gradient as the cumulative curves of the accompanying zircon and chromite fractions (the latter two minerals being of undoubted detrital origin). The only explanation for such well-matched size distributions is that the minerals are in hydraulic equilibrium, and that the uraninite grains were deposited together with the zircon and chromite fractions from a suspension in water.

In addition to the visual method, the hydraulic equilibrium between mineral fractions can be shown to exist by calculating the ratios between the median grain-size of minerals of about the same specific gravity, and the median grain size of minerals of a higher or lower specific gravity. If the calculated ratios do not vary much from place to place, even though the median grain-sizes and sorting may be variable, then it can be deduced that the minerals are in hydraulic equilibrium. If the specific gravities of the minerals under comparison are known, then a theoretical ratio can be calculated, according to Stoke's formula. This ratio should not vary significantly from the observed ratio. Koen (1961) found that the theoretical ratios between the sizes of equally settling uraninite and zircon (or chromite) grains, and uraninite and quartz grains are very similar to the observed ratios, and concluded that the minerals mentioned are in hydraulic equilibrium with each other.

Rittenhouse (1943) determined the so-called hydraulic equivalents of a number of heavy minerals (see table below). The hydraulic equivalent is the number of Udden size grades (1 Udden size grade on the unmodified scale equals 1.0 phi units) between the median grain-size of a given heavy mineral and the median grain-size of quartz, with which it was deposited, and to which it is hydraulically equivalent. For coarser sands, where Stoke's Law fails, the hydraulic equivalent ratio is not the same (Pettijohn, 1957). Rittenhouse (1943) determined the hydraulic equivalents for each size grade over a range of hydraulic equivalent sizes from 0.0 ϕ to 1.0 ϕ. In determining these sizes, the phi (ϕ) value, where the variation was smallest, was considered to be the true hydraulic equivalent size, but even for the best ϕ value, which represented the average of a number of size grades, unexplained variations were apparent. These variations were caused by chance errors in sampling, and, to some extent, by some unknown factor or factors.

Mineral	S.G.	Best Values of Hydraulic Equivalents i.e. number of ∅ units < quartz, for all sizes
Magnetite	5.2	1.0
Ilmenite	4.7	1.0
Zircon	4.6	.9
Titanite	3.5	.5
Apatite	3.2	.4
Tourmaline	3.1	.2

THE QUANTITATIVE MINERALOGICAL PROPERTIES OF THE MAIN REEF AND MAIN REEF LEADER

A. VOLUMETRIC COMPOSITION OF THE MATRIX

(a) The Overall Proportions of Minerals

The matrix material of the reefs under investigation is, in general, very similar. Quartz of both allogenic and authigenic origin occurs in great abundance in all thin-sections studied, and may often effectively mask significant variations in the relative percentages of the minor constituents. In an attempt to indicate and accentuate differences in the mineralogy of the matrix, from one sample to another, and from reef to reef, use has been made of ternary diagrams, using different combinations of particular matrix materials.

The following data is presented in Table I :

(i) the relative percentages of the phyllosilicates;

(ii) the relative percentages of quartz, sericite, and iron magnesian silicates (chlorite and chloritoid); and

(iii) the relative percentages of sand, silt, and phyllosilicates.

TABLE I : RELATIVE PERCENTAGES OF MATRIX MATERIAL

(i) Relative Percentages of Phyllosilicates

1. Main Reef Leader (East Rand)

Locality	Sericite + Pyrophyllite	Chlorite	Chloritoid
Modder East k4701 - k4707	89.62	10.29	-
Modder East k4710 - k4714	66.36	33.61	-
Van Dyk	96.15	3.82	-
East Geduld	100.00	-	-
Geduld	100.00	-	-
Vlakfontein	73.60	26.40	-
Vogelstruisbult	31.81	68.17	-
Spaarwater	67.21	32.78	-
Sub Nigel	32.46	67.40	-
East Daggafontein	18.86	81.14	-
Daggafontein	13.50	86.49	-
Grootvlei	97.20	2.80	-
S.A. Lands	79.40	20.60	-
Marievale	82.68	17.31	-

2. Main Reef Leader (Central Rand)

Locality	Sericite + Pyrophyllite	Chlorite	Chloritoid
Crown Mines 5	49.78	20.10	29.96
Crown Mines 6	46.87	3.13	50.00
Crown Mines 7a	81.35	-	18.64
Crown Mines 7b	93.10	-	6.89
Crown Mines 7c	87.80	-	12.20
Crown Mines 7d	78.12	-	21.87
Crown Mines 8b	51.24	27.50	21.24
Crown Mines 8c	27.69	24.61	47.69
Crown Mines 8d	41.70	39.40	18.70
E.R.P.M. 9 (Composite Reef)	-	76.60	23.00
E.R.P.M. 2	-	75.10	25.00
Rose Deep 6	3.27	96.73	-
C.M.R. 4	51.42	42.85	5.71

3. Main Reef (West Wits Line, West Rand, Central Rand)

Locality	Sericite + Pyrophyllite	Chlorite	Chloritoid
Doornfontein	47.25	47.75	5.00
West Driefontein	72.72	27.27	-
Libanon	45.87	47.99	6.11
Venterspost	36.06	29.62	34.80
West Rand Cons.	25.72	7.34	66.90
Luipaardsvlei	33.73	2.40	63.35
Durban Deep	26.78	1.58	71.60
C.M.R.	46.87	9.37	43.75
City Deep	34.60	43.13	22.25
Rose Deep	20.13	72.91	6.94
E.R.P.M.	18.76	62.36	18.33

(ii) Relative Percentages of Quartz, Sericite, and Iron-Magnesian Silicates (Chlorite and Chloritoid)

1. Main Reef Leader (East Rand)

Locality	Quartz	Sericite	Fe-Mg Silicates
Modder East k4701 - k4707	89.95	8.61	1.42
Modder East k4710 - k4714	86.22	9.30	4.10
Van Dyk	86.28	13.22	.47
East Geduld	90.75	8.50	-
Geduld	94.56	5.43	-
Vlakfontein	89.70	7.45	2.72
Vogelstruisbult	86.33	4.76	8.88
Spaarwater	87.32	9.15	3.49
Sub Nigel	77.66	6.22	16.84
East Daggafontein	81.07	3.57	15.35
Daggafontein	77.30	3.06	19.63
Grootvlei	87.50	12.16	.33
S.A. Lands	80.63	15.48	3.87
Marievale	89.10	8.62	2.25

2. Main Reef Leader (Central Rand)

Crown Mines 5	89.64	5.05	5.30
Crown Mines 6	86.14	6.49	7.35
Crown Mines 8b	72.50	14.08	13.40
Crown Mines 8c	77.27	5.11	17.61
Crown Mines 8d	88.86	4.65	6.48
Crown Mines 7a	76.49	19.12	4.38
Crown Mines 7b	85.57	13.43	1.00
Crown Mines 7c	94.25	5.00	.75
Crown Mines 7d	90.00	7.81	2.18
E.R.P.M. 9 (Composite Reef)	75.87	-	24.22
E.R.P.M. 2	71.45	-	28.54
Rose Deep	73.85	.85	25.28
C.M.R. 4	73.48	13.63	12.87

3. Main Reef (West Wits Line, West Rand, Central Rand)

Doornfontein	90.58	4.47	4.94
West Driefontein	97.20	2.03	.76
Libanon	76.40	10.83	12.67
Venterspost	87.00	4.76	7.97
West Rand Cons.	85.30	3.21	11.10
Luipaardsvlei	74.46	8.61	16.92
Durban Deep	74.09	6.92	18.97
C.M.R.	90.61	4.39	4.98
City Deep	83.73	3.72	12.52
Rose Deep	68.89	4.98	26.11
E.R.P.M.	72.98	5.02	21.98

(iii) Relative Percentages of Sand, Silt, and Phyllosilicates

1. Main Reef Leader (East Rand)

Locality	Sand	Silt	Phyllosilicates
Modder East k4701 - k4707			
Modder East k4709 Intercalated Qtz.	79.85	11.75	8.39
Modder East k4710 - k4713			
Van Dyk	61.61	26.06	12.32
East Geduld	69.18	22.55	8.28
Geduld	60.86	33.69	5.43
Vlakfontein	75.13	14.81	10.03
Vogelstruisbult	70.49	15.83	13.65
Spaarwater	57.68	29.63	12.66
Sub Nigel	58.08	20.15	21.72
East Daggafontein	72.50	8.57	18.92
Daggafontein	65.03	12.26	22.69
Grootvlei	58.37	28.67	12.93
S.A. Lands	59.91	21.13	18.93
Marievale	66.69	23.43	9.85

2. Main Reef Leader (Central Rand)

Crown Mines 5	70.45	19.19	10.33
Crown Mines 6	70.56	15.58	13.84
Crown Mines 7b	68.40	17.16	14.43
Crown Mines 7c	68.10	26.15	5.74
Crown Mines 7d	69.56	20.49	9.93
Crown Mines 8a	53.95	18.55	27.48
Crown Mines 8c	64.37	16.32	19.27
Crown Mines 8d	64.00	21.00	15.00
E.R.P.M. 9 (Composite Reef)	54.70	20.70	24.40
E.R.P.M. 2	49.14	22.31	28.54
Rose Deep	40.28	33.57	26.14
C.M.R.	51.51	21.96	26.51

3. Main Reef (West Wits Line, West Rand, Central Rand)

Doornfontein	76.47	14.11	9.41
West Driefontein	88.80	8.39	2.79
Libanon	58.16	18.30	23.51
Ventersport	75.85	11.41	12.71
West Rand Cons.	76.67	8.92	14.28
Durban Deep	64.67	9.42	25.89
Luipaardsvlei	60.00	14.46	25.53
C.M.R.	71.84	18.76	9.38
City Deep	70.57	13.15	16.25
Rose Deep	58.73	10.16	31.10
E.R.P.M.	61.99	10.99	27.00

(b) Relative Percentages of the Phyllosilicates

Variations in the relative percentages of the phyllosilicates, sericite (plus muscovite and pyrophyllite), chlorite, and chloritoid, from reef to reef are of significance. These variations are depicted graphically in the ternary plots, shown in Figure 2A a, b, c and d.

The complete lack of chloritoid within the matrix is the most distinctive feature of the Main Reef Leader (East Rand). The phyllosilicates consist entirely of chlorite and sericite in varying proportions. Sericite usually predominates over chlorite, and in most cases constitutes over 60% of the total phyllosilicates present. In only four cases does chlorite constitute more than 60% of the total. The percentages of these two minerals are variable, and no patterns are apparent. Sericite, chlorite, and chloritoid occur to a varying extent in the Main Reef Leader of the Central Rand. Sericite is the most abundant phyllosilicate in a number of samples, but the high content of chlorite in the E.R.P.M. - Rose Deep area is distinctive. Chloritoid occurs in all but one of the samples studied. The distribution of this mineral is, in general, erratic. As in the case of the Main Reef Leader of the Central Rand, the three phyllosilicates under discussion are prominent in the matrix of the Main Reef. Whereas the sericite content remains fairly constant, there is a large variation in the chlorite and chloritoid percentages. The chloritoid content varies from 71.6% of the phyllosilicates at the Durban Deep Mine to zero at West Driefontein. Similarly, the relative percentage of chlorite varies from 1.58% at Durban Deep to 72.91% at Rose Deep. The high percentage of chlorite at Rose Deep and E.R.P.M. is again apparent. Unlike the chlorite and chloritoid in the Main Reef Leader, there appears to be an antipathetic relationship between chlorite and chloritoid in the Main Reef, i.e. with a high percentage of chloritoid in the matrix, there is generally a low percentage of chlorite, and vice versa. There appears to be, in addition, a build-up in the chloritoid content of the matrix from the Doornfontein Mine in the south to the mines in the vicinity of Krugersdorp. A similar build-up from the E.R.P.M. - Rose Deep area to the Krugersdorp area is also apparent. The above features are demonstrated by means of histograms in Figure 3A. Calculations of the relative percentages of phyllosilicates occurring within the South Reef were made on five samples from the Central Rand. Although chloritoid is present in this reef, it appears to be of minor importance, and never constitutes more than 13% of the total phyllosilicates. The sericite and chlorite content of the reef is variable. It is apparent that the phyllosilicate content of this reef is more similar to the phyllosilicate content of the Main Reef Leader (East Rand) than to that of the Main Reef or Main Reef Leader.

Chloritoid forms most commonly as a metamorphic mineral, and the original composition of the interstitial mud, rather than temperature or stress, is the most important prerequisite for 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 the composition of similar material in the matrix of the Main Reef and Main Reef Leader.

The type of phyllosilicate occurring within the matrix of a particular reef is probably related to a certain degree to the composition of the underlying footwall horizon. In the Central Rand area, for example, the Main Reef Leader often lies directly on the Black Bar which contains an abundance of chloritoid. In such instances, the matrix of the overlying reef invariably contains chloritoid. In the area of the West Rand Consolidated Mine, the Main Reef footwall horizon usually consists of a quartzite. Microscopic examination reveals that this quartzite contains abundant chloritoid crystals, and the overlying Main Reef is characterized by a prolific development of chloritoid in its matrix. The Jeppestown shale is the most common footwall horizon (except where eliminated by footwall erosion channels) of the Main Reef Leader (East Rand). All thin-sections of this shale examined during the present investigation revealed that the dominant phyllosilicates are sericite and chlorite, in varying proportions. No chloritoid was noted. Strydom (1952) recognized two types of Jeppestown shale in the East Rand. A green quartzitic shale lies directly below the reef horizon, and contains a preponderence of sericite over chlorite. This green shale grades into a grey quartzitic shale which consists dominantly of chlorite, with small amounts of sericite. Although no chloritoid has been described from the Jeppestown shale, the mineral has been observed in the channel footwall beds.

It is evident that, in the case of the Black Bar at least, the original material must have been of a fairly soft, clayey nature at the time of reef deposition. Irregular blebs of Black Bar material are common in the reef. It is probable that at the time of conglomerate formation, small particles of semi-consolidated clay were incorporated in the interstitial mud. The disposition of many of the pebbles lying directly on the Black Bar also seems to suggest that the latter material was in a semi-plastic condition at the time of reef deposition. Similar conditions were probably present in the depositional area of the Main Reef Leader (East Rand). It is possible that the quartzite footwall of the Main Reef was only partly consolidated at the time of introduction of the reef material.

The presence or absence of chloritoid in a particular reef is dependent partly on the composition of the footwall, and partly on the composition of the original clayey material brought into the depositional basin together with other conglomerate constituents, probably in the form of interstitial mud.

Microscopic examination reveals that chloritoid, by virtue of its porphyroblastic nature and association with other minerals, must have been one of the first phyllosilicates to crystallize. It is envisaged that chloritoid crystallized under metamorphic conditions, providing the composition of the interstitial material was suitable (i.e. a high Al_2O_3 and FeO content). As the composition of the original material changed with the subtraction of Al_2O_3 and FeO, or if these compounds were originally not abundant, chlorite formed and possibly surrounded chloritoid crystals. Thus, the observed decrease in the chloritoid content of the matrix of the Main Reef in an easterly and southerly direction from mines in the Krugersdorp area could possibly be a reflection of a progressive change in composition of interstitial mud from a major entry point of reef material somewhere northwest of Krugersdorp. According to Pettijohn (1957), there appears to be a progressive increase in potash and magnesia in muds, with increasing distance from shore. With this increase, a corresponding increase in chlorite and illite might be expected, at the expense of the more aluminium-rich material, which would presumably be concentrated near the shore.

The percentage of sericite in the reefs under investigation remains relatively constant. The mineral is extremely widespread, and occurs in nearly every thin-section examined. The relative abundance of the mineral in the Main Reef Leader (East Rand) probably reflects the composition of the original interstitial matrix material. It is probable that most of the sericite has been derived from the reconstitution of interstitial mud under conditions of metamorphism, plus the breakdown of felspars under conditions of stress and normal decomposition. In general, it can be said that the occurrence of sericite in the matrix, in abundance, is a reflection of generally acidic rocks in the source area, whereas chlorite and chloritoid in the matrix are probably a manifestation of more basic rocks in the source area.

(c) Relative Percentages of Quartz, Sericite, and Iron-Magnesian Silicates

Quartz (sand + silt + authigenic material) is by far the most abundant mineral of the matrix, of which it almost invariably constitutes more than 70%, and in most cases more than 80% of the total. Although the great abundance of quartz tends to conceal any differences which may exist amongst the phyllosilicates, actual differences are apparent from reef to reef (see Figure 4a, b, and c).

In general, the Main Reef Leader (East Rand) contains an abundance of quartz with a predominance of sericite over iron-magnesian silicates (see Figure 4a). In this respect, it differs considerably from the Main Reef, which, with a variable content of quartz, contains an abundance of iron-magnesian silicates over sericite (see Figure 4b). The Main Reef Leader (see Figure 4c) contains a variable percentage of all three components, and is intermediate between the Main Reef and Main Reef Leader (East Rand) in this respect.

(d) Relative Percentages of Sand, Silt, and Phyllosilicates

No differences between the sand, silt, and phyllosilicate content of the reefs under examination is apparent. The predominance of quartz and the difficulty of distinguishing the silt fraction from quartz of authigenic origin make comparisons between reef horizons a doubtful aid to correlation. For this reason, all results were plotted on a single ternary diagram (see Figure 4d). Besides indicating the general composition of the matrix, this diagram has the advantage of indicating approximately under what conditions the conglomerates must have been deposited. Comparison with diagrams given by Weller (1960), in which sand, silt, and clay (corresponding to iron-magnesian silicates, possibly with some sericite) were plotted on three-component diagrams, indicates that the sediments under investigation were possibly deposited in near-shore (littoral) to inner shelf (neritic) environments.

B. THE RELATIVE PROPORTIONS OF THE ORE MINERALS

(a) The Overall Proportions of the Minerals

The relative percentages of all the ore minerals (i.e. all the sulphides, gold, carbon, and uraninite) are represented in Table II. The tenor of gold concentration is given for samples where this information was available. The proximity of dykes to the various samples is also given, as well as general remarks concerning the disposition of the reef, where such data accompanied the samples. It should be noted that, in some cases, the percentage given obviously represents the mineral assemblage over a very limited area of reef. In most instances, however, it is apparent that the relative percentages are representative of fairly large areas of reef. Generally, where a number of samples have been taken over a fairly large area, the ore mineralogy remains fairly constant. In order to show the similarities and dissimilarities of the ore mineralogy over a few feet of reef, the percentage composition of the ore minerals are given for all the samples from each locality, where possible.

(b) Areal Variations in the Content of Ore Minerals

The mineralization of the Main Reef Leader (East Rand) is generally intense, and in many cases a large part of the matrix is composed of sulphides. The major sulphide is pyrite (of all varieties), which occurs in about 95% of the samples studied.

The amounts of this mineral are, however, very variable. In a few instances it is the only ore mineral present in a particular section, but in other cases it may be entirely absent. Pyrrhotite is a very abundant constituent of the reef, and was observed in about 80% of the sections examined. Like pyrite, the pyrrhotite content is variable. The mineral constitutes over 90% of the total ore minerals in roughly 10% of the sections examined, but usually comprises less than 5% of the total. The antipathetic relationship between pyrite and pyrrhotite is marked, so that high percentages of pyrite are usually accompanied by low percentages of pyrrhotite, and vice versa. Since either pyrite or pyrrhotite is the major mineral in a particular section, all the other constituents, as far as relative percentages are concerned, are of minor importance. Anomalously high values of one, or more, of these constituents are few. Although rarely constituting more than 2% (maximum under 6%) of the total, rounded grains of arsenopyrite (plus rounded glaucodot and cobaltite) are very persistent throughout the Main Reef Leader (East Rand). These minerals, which are of different origin to their hydrothermal or "pseudo-hydrothermal" counterparts, were observed in 50% of the polished sections examined. The wide-spread distribution in all the reefs studied is distinctive. As in the case of arsenopyrite, thucholite, mainly in the form of rounded pillules, is a wide-spread component of the reef, occurring in just under 50% of samples studied. In some cases, it may constitute up to 19% of the total ore minerals, but it is usually much less abundant. Uraninite is generally not conspicuous, but may be important in some areas. Chalcopyrite occurs to about the same extent as thucholite, but in some instances, it may be very important, and may comprise up to 46% of the ore minerals. Small amounts of chalcopyrite are often associated with pyrrhotite. Gold, gersdorfite, and cobaltite, the latter two minerals being of the secondary variety, are generally inconspicuous. Gold is observed to a varying extent in a number of sections, and may sometimes figure in the count of ore minerals. In some exceptionally rich samples, gold may be the dominant ore mineral, but such cases are rare and very local.

In the case of the Main Reef Leader (Central Rand), mineralization is usually fairly intense, and a variety of ore minerals is present. Pyrite is the most abundant mineral, and generally constitutes over 90% of the total. The mineral occurs in all the sections examined. Pyrrhotite occurs in about 50% of the samples studied, but it is not as conspicuous as in the Main Reef Leader (East Rand). It may constitute over 40% of the ore minerals, but usually occurs in minor amounts (up to 4%). Rounded grains of arsenopyrite (plus glaucodot and cobaltite) may be fairly abundant in some sections, but are generally less conspicuous than in the Main Reef Leader (East Rand). Of interest is the occurrence of large irregular patches of gersdorfite, with some cobaltite, which constitute over 20% of the total ore minerals. Chalcopyrite is a common, though minor, constituent in the reef, and is often closely associated with pyrrhotite. It occurs in about 50% of the samples examined. Carbon and uraninite occur with much the same frequency as in the Main Reef Leader (East Rand). In exceptional cases, carbon may constitute over 70% of the total ore minerals. Gold is present in most of the sections examined, and may be relatively plentiful in some areas, where it may constitute up to 3% of the total ore minerals. There is a marked tendency for gold to be more abundant in samples rich in carbon, and in samples taken from footwall contacts.

The most distinctive feature of the Main Reef is the occurrence of pyrite to the almost complete exclusion of other ore minerals. In all but two of the sections examined, pyrite accounts for more than 98% of the total ore minerals. In only two cases does pyrrhotite constitute more than 10% of the total, and for the rest is present in very minor amounts only. In comparison with the other reefs studied, the variety of ore minerals present in a particular sample is limited. Arsenopyrite (plus glaucodot and cobaltite), in rounded form, is the most persistent mineral (besides pyrite), and occurs in about 50% of the samples. It is especially noticeable in the West Wits Line. Chalcopyrite, thucholite, and uraninite are generally of minor importance, and gold is not nearly as common as in the Main Reef Leader (Central Rand) or the Main Reef Leader (East Rand).

TABLE II : RELATIVE PERCENTAGES OF THE ORE MINERALS

(i) Main Reef Leader (East Rand)

Locality and Sample	Pyrite	Pyrrhotite	Chalcopyrite	Arsenopyrite, Glaucodot, and Rounded Cobaltite	Thucholite	Uraninite	Gersdorfite	Secondary Cobaltite	Gold	Tenor of Gold	Proximity of Dykes	Remarks
Modder East k4701	-	95.11	.74	.29	2.96	-	-	-	.29	high	Four samples taken approx. 100' from dyke	Four samples taken from foot-wall contact
Modder East k4702	2.43	90.18	2.7	.10	1.89	-	-	-	.067	high		
Modder East k4703	-	98.17	.51	-	.51	-	-	-	.25	high		
Modder East k4704	3.62	90.53	5.25	-	.54	-	-	-	.045	high		
Modder East k4705	-	96.68	-	.05	1.98	-	-	-	.32	high	Three samples taken approx. 100' from dyke	Three samples taken in upper reef bands
Modder East k4706	88.54	8.59	-	2.86	-	-	-	-	-	average		
Modder East k4707	91.49	1.02	.34	5.78	1.36	-	-	-	-	average		
Modder East k4710	81.69	-	12.2	.46	5.63	-	-	-	-	high		Four samples taken from foot-wall band of reef
Modder East k4711	63.9	-	21.3	.59	14.2	-	-	-	-	high		
Modder East k4713	30.35	1.78	46.42	1.78	19.64	-	-	-	-	high		
Modder East k4714	73.61	-	6.94	-	19.44	-	-	-	-	high		
Van Dyk 3	-	82.8	3.82	.63	11.46	1.27	-	-	-	30 dwts./ton		-
East Geduld 7	97.13	1.59	-	1.27	-	-	-	-	-	2000 dwts./ton		-
East Geduld 4	100.00	-	-	-	-	-	-	-	-	290 dwts./ton		-
Geduld 1	2.98	95.57	-	1.49	-	-	-	-	-	60 dwts./ton		-
Vlakfontein 7	.67	96.48	.50	.67	1.67	-	-	-	-	60 dwts./ton	Four samples taken in area where quartz dolerite dyke occur; nearest intrusive 50'	Area on flank of anticline
Vlakfontein 8	.33	99.33	-	-	.33	-	-	-	-	60 dwts./ton		
Vlakfontein 9	-	99.42	-	.19	.38	-	-	-	-	60 dwts./ton		
Vlakfontein 10	-	98.24	-	.07	1.68	-	-	-	-			
Vogelstruisbult 20	97.75	-	.1	-	-	2.13	-	-	-	40 dwts./ton		500' north of major fault
Vogelstruisbult 22	96.94	1.18	-	.29	-	1.57	-	-	-	40 dwts./ton		
Spaarwater 2	99.32	.13	.27	.13	.13	-	-	-	-	130 dwts./ton		On flank of anticline
Spaarwater 3a	99.21	.15	-	.18	.47	-	-	-	-	130 dwts./ton		
Spaarwater 5a	100.00	-	-	-	-	-	-	-	-	130 dwts./ton		
Sub Nigel 14	100.00	-	-	-	-	-	-	-	-	10 dwts./ton		On flank of syncline
Sub Nigel 15	97.11	.41	2.46	-	-	-	-	-	-	10 dwts./ton		
Sub Nigel 16	67.51	25.47	.63	1.69	-	4.24	-	-	.42	10 dwts./ton		
East Daggafontein 1a	98.53	-	-	-	-	1.47	-	-	-	25 dwts./ton	Three samples taken 600' from Karroo dyke	-
East Daggafontein 1b	89.84	.3	-	-	-	8.61	-	-	1.23	-		
East Daggafontein 1c	83.33	-	-	-	-	15.47	-	-	1.19	-		
Daggafontein 1a	97.59	.41	.60	.10	.39	.82	-	-	-	24 dwts./ton	Two samples taken 20' from dyke	-
Daggafontein 1b	97.62	.2	.3	.05	1.4	.35	-	-	-	-		
Grootvlei 7	93.91	3.0	1.49	.093	1.49	-	-	-	-	22 dwts./ton		-
Grootvlei 7a	97.13	1.27	-	-	1.59	-	-	-	-	22 dwts./ton		
S.A. Lands 2	100.00	-	-	-	-	-	-	-	-	20 dwts./ton	Three samples taken 15'-30' from ilmenite diabase dyke	-
S.A. Lands 2a	99.5	.5	-	-	-	-	-	-	-	20 dwts./ton		
S.A. Lands 3	100.00	-	-	-	-	-	-	-	-	-		
Marievale 1a (i)	85.88	13.21	.42	.63	.35	-	-	-	-	11 dwts./ton		
Marievale 1a (ii)	83.33	16.67	-	-	-	-	-	-	-	11 dwts./ton		
Marievale 1b	37.74	59.38	.24	1.00	.20	1.25	-	-	.20	10 dwts./ton		
Marievale 1c (i)	39.06	57.81	1.40	1.56	-	-	-	-	-	10 dwts./ton		
Marievale 1c (ii)	64.72	32.36	-	1.29	1.61	-	-	-	-	10 dwts./ton		
Marievale 1e	39.8	59.7	-	.49	-	-	-	-	-	10 dwts./ton		

TABLE II (Continued)

(ii) Main Reef Leader (Central Rand)

Locality and Sample	Pyrite	Pyrrhotite	Chalcopyrite	Arsenopyrite, Glaucodot and Rounded Cobaltite	Thucholite	Uraninite	Gersdorfite	Secondary Cobaltite	Gold	Tenor of Gold	Proximity to Dykes	Remarks
Crown Mines 5	97.26	1.51	1.21	-	-	-	-	-	-	high		Well-developed reef
Crown Mines 6	96.7	-	-	-	2.93	-	-	-	2.50	low		Poorly developed reef
Crown Mines 7a	61.9	1.9	.75	2.0	15.00	.97	14.78	1.5	-	average		Reef on Black Bar
Crown Mines 7b	53.84	.76	13.84	.50	7.69	-	23.07	.26	-	low		Reef on Black Bar
Crown Mines 7d	97.22	2.78	-	-	-	-	-	-	-	low		Reef on Black Bar
Crown Mines 8a	98.89	-	-	.73	-	-	.50	-	.36	high		-
Crown Mines 8b	99.07	-	-	.46	-	-	-	-	.46	low		-
Crown Mines 8c	77.09	4.4	13.65	-	1.32	.05	-	-	3.40	average		-
Crown Mines 8d	79.09	20.9	-	-	-	-	-	-	-	low		-
Crown Mines 8e	100.00	-	-	-	-	-	-	-	-	high		-
E.R.P.M. 2	56.16	43.15	.68	-	-	-	-	-	-	5 dwts./ton	-	-
E.R.P.M. 11	23.4	2.16	.21	-	73.13	-	-	-	1.50	20 dwts./ton		Patches rich in carbon
C.M.R. 4	97.99	-	.4	.25	1.4	-	.15	-	-	100 dwts./ton	-	-
City Deep 6	96.6	-	1.69	-	1.5	-	-	-	-	10 dwts./ton	-	-

(iii) Main Reef (West Wits Line, West Rand, Central Rand)

Locality and Sample	Pyrite	Pyrrhotite	Chalcopyrite	Arsenopyrite, Glaucodot and Rounded Cobaltite	Thucholite	Uraninite	Gersdorfite	Secondary Cobaltite	Gold	Tenor of Gold	Proximity to Dykes	Remarks
Doornfontein 12	99.86	-	-	.14	-	-	-	-	-	15 dwts./ton	-	-
West Driefontein 11	99.21	-	-	-	.79	-	-	-	-	2 dwts./ton	-	-
Libanon 8	98.59	-	-	.41	-	-	-	-	-	4 dwts./ton	-	-
Libanon 9	99.81	-	-	.19	-	-	-	-	-	4 dwts./ton		
Libanon 10	99.52	.16	-	.31	-	-	-	-	-	4 dwts./ton		
Venterspost 1	99.01	.10	.05	.80	-	-	-	-	-	7 dwts./ton	-	-
Venterspost 3	99.7	-	-	.30	-	-	-	-	-	7 dwts./ton		
West Rand Cons. 1	99.3	-	.29	-	.39	-	-	-	-	22 dwts./ton	-	Highly faulted area
West Rand Cons. 8	100.00	-	-	-	-	-	-	-	-	-	-	
Durban Deep 1	100.00	-	-	-	-	-	-	-	-	9 dwts./ton	-	-
Durban Deep 3	100.00	-	-	-	-	-	-	-	-	9 dwts./ton	-	-
Luipaardsvlei	99.15	-	-	-	-	-	-	-	-	-	-	-
C.M.R. 5	99.55	-	-	-	.45	-	-	-	-	10 dwts./ton	-	-
City Deep	97.47	-	.16	-	-	1.30	-	-	.84	4 dwts./ton	-	-
Rose Deep 10	99.37	-	-	.63	-	-	-	-	-	12 dwts./ton	-	-
E.R.P.M. 4	98.46	1.02	.51	-	-	-	-	-	-	-	-	-
E.R.P.M. 5	76.43	17.19	6.36	-	-	-	-	-	-	-		
E.R.P.M. 7	77.72	20.52	1.46	.12	.16	-	-	-	-	-		

It is apparent from the above results that there are major differences in the ore mineralogy of the three reefs studied. Whereas the Main Reef Leader (East Rand) and the Main Reef Leader (Central Rand) contain large amounts of pyrrhotite, especially the former reef, the Main Reef is singularly free of this mineral. It therefore seems likely that the conditions conducive to the formation of pyrrhotite were not developed in the Main Reef horizon. The only pyrrhotite present in the latter reef is in the form of minute flakes and veinlets, often associated with grains of uraninite or leucoxene. It seems likely that this pyrrhotite had a different origin to the large masses of pyrrhotite sometimes found in the Main Reef Leader (East Rand), which, in places, constitute more than 90% of the total ore minerals. In addition to the significant amounts of pyrrhotite, the Main Reef Leader (East Rand) and the Main Reef Leader (Central Rand) contain a relatively large variety of ore minerals. Thucholite, chalcopyrite, and irregular masses of gersdorfite may be well represented in some areas. Uraninite is often conspicuous in both horizons, and tends to be concentrated along footwall contacts. The only mineral which occurs relatively constantly throughout the reef horizons studied, excluding pyrite, is arsenopyrite (plus glaucodot and cobaltite).

C. THE RELATIVE PROPORTIONS OF THE HEAVY MINERALS

(a) Overall Proportions of the Minerals

In this study, the relative percentages of the three most commonly occurring heavy minerals, viz. zircon, chromite, and leucoxene, were calculated from number counts. The results obtained for each particular reef horizon were plotted on three-component and two-component scatter diagrams, to indicate similarities and dissimilarities between reefs. Table III represents the average of a large number of grains counted from every sample.

TABLE III : RELATIVE PERCENTAGES OF ZIRCON, CHROMITE, AND LEUCOXENE

(i) Main Reef Leader (East Rand)

Locality	Zircon	Chromite	Leucoxene
Modder East a	17.64	10.69	71.24
Modder East b	17.01	12.09	71.20
Van Dyk	24.28	4.28	71.42
East Geduld	12.10	7.69	80.20
Geduld	12.59	11.44	75.91
Vlakfontein	20.50	14.55	64.86
Vogelstruisbult	21.23	26.52	52.15
Spaarwater	19.14	12.32	68.30
Sub Nigel	11.96	11.82	76.11
East Daggafontein	31.61	36.83	31.50
Daggafontein	16.19	8.47	75.37
Grootvlei	19.31	15.34	65.62
S.A. Lands	13.74	10.02	76.21
Marievale	25.60	20.40	54.00

(ii) Main Reef Leader (Central Rand)

Locality	Zircon	Chromite	Leucoxene
Crown Mines 5	28.32	1.76	70.00
Crown Mines 6	29.39	5.55	65.04
Crown Mines 7a	48.43	2.73	48.82
Crown Mines 7d	54.62	1.08	44.61
Crown Mines 8a	26.40	3.60	70.03
Crown Mines 8b	26.42	3.38	70.18
Crown Mines 8c	30.09	4.84	65.05
Crown Mines 8d	23.71	4.47	71.80
Crown Mines 8e	29.49	5.98	64.52
E.R.P.M. 2	17.24	1.52	80.77
Rose Deep	32.69	7.69	59.61
C.M.R.	30.33	7.20	62.46
City Deep	52.30	1.88	44.98

(iii) Main Reef (West Wits Line, West Rand, Central Rand)

Doornfontein	27.73	15.64	56.25
West Driefontein	22.86	36.21	40.92
Libanon	33.55	22.27	44.26
Venterspost	24.77	12.92	62.38
West Rand Cons.	43.90	7.95	44.95
Luipaardsvlei	42.00	4.84	53.20
Durban Deep	33.58	8.63	57.70
C.M.R.	26.69	13.50	59.79
City Deep	25.45	5.09	69.45
Rose Deep	40.63	8.43	50.92
E.R.P.M.	28.57	7.28	64.44

(b) Variations in Composition between Reefs

The three-component plot (Figure 5a) of the Main Reef Leader (East Rand) indicates that all points, except three, fall into a well-defined, slightly elongated zone. The average percentage of the various components were calculated as follows :-

leucoxene	66.72%
zircon	18.78%
chromite	14.46%
	99.90%

These percentages agree closely with those obtained by Whiteside (1944) for the same reef over an area representing roughly the central portion of the East Rand. He obtained his results by crushing samples of reef, and analyzing the heavy minerals after separation with bromoform. The maximum variations in the relative percentages of the various heavy minerals are given below as (i) including all samples, and (ii) including only those samples with a normal distribution (i.e. occurring within the area defined by the continuous line (in Figure 5a) :-

(i)		(ii)	
leucoxene	48.70%	leucoxene	16.06%
zircon	19.65%	zircon	12.32%
chromite	32.55%	chromite	11.06%

It is obvious from these results that the three points occurring outside the main concentration of points affect the relative percentages of the heavy minerals to a marked extent. In order to analyse these variations, or anomalous results, the percentages of chromite against leucoxene, zircon against leucoxene, and chromite against zircon were plotted on two-component diagrams (see Figure 5b, c, and d). In these plots, a linear trend (indicated by discontinuous lines) is apparent. In the case of the leucoxene-chromite plot, confirmation of this trend was obtained by calculating the correlation coefficient (Moroney, 1962), giving a statistical appraisal of the chances of the line (or linear pattern) obtained being a straight-line function, as .73. This trend signifies that, whereas the relative percentages of chromite and zircon remain fairly constant, there is a more marked variation in the relative percentages of leucoxene. The percentages of zircon and chromite tend to vary sympathetically.

From the three-component plot (Figure 6a) representing the relative proportions of the heavy mineral components of the Main Reef Leader (Central Rand) it is seen that, as with the Main Reef Leader (East Rand), there is a marked concentration of points, giving a slightly elongated pattern (indicated by a continuous black line). As in the case of the Main Reef Leader (East Rand), three plots fall well outside the main concentration of points. The anomalous points in this and the Main Reef Leader (East Rand) will be discussed later. The average percentage of the heavy mineral components is :-

leucoxene	62.80%
zircon	32.95%
chromite	3.93%
	99.68%

Variations in the relative percentages are given as (i) including all samples, and as (ii) including only those samples occurring within the solid black line of Figure 6a :-

(i)		(ii)	
leucoxene	36.79%	leucoxene	21.16%
chromite	4.90%	chromite	6.17%
zircon	37.38%	zircon	15.45%

The effect of the three anomalous points on the percentage composition of the constituents is as marked as in the case of the Main Reef Leader (East Rand). To analyse these variations, two-component plots of all constituents were made. From these plots (Figures 6b, c, and d) it is seen that linear trends are again apparent. The same relationship between the relative percentages of the heavy minerals, as outlined for the Main Reef Leader (East Rand), appears to hold.

The three-component plot depicting the relative percentages of leucoxene, chromite, and zircon in the Main Reef is shown in Figure 7a. There is no marked concentration of the plots, as in the other two reefs, and the points tend to be scattered. The average content of the heavy minerals is as follows :-

(i)		(ii)	
leucoxene	48.70%	leucoxene	16.06%
zircon	19.65%	zircon	12.32%
chromite	32.55%	chromite	11.06%

It is obvious from these results that the three points occurring outside the main concentration of points affect the relative percentages of the heavy minerals to a marked extent. In order to analyse these variations, or anomalous results, the percentages of chromite against leucoxene, zircon against leucoxene, and chromite against zircon were plotted on two-component diagrams (see Figure 5b, c, and d). In these plots, a linear trend (indicated by discontinuous lines) is apparent. In the case of the leucoxene-chromite plot, confirmation of this trend was obtained by calculating the correlation coefficient (Moroney, 1962), giving a statistical appraisal of the chances of the line (or linear pattern) obtained being a straight-line function, as .73. This trend signifies that, whereas the relative percentages of chromite and zircon remain fairly constant, there is a more marked variation in the relative percentages of leucoxene. The percentages of zircon and chromite tend to vary sympathetically.

From the three-component plot (Figure 6a) representing the relative proportions of the heavy mineral components of the Main Reef Leader (Central Rand) it is seen that, as with the Main Reef Leader (East Rand), there is a marked concentration of points, giving a slightly elongated pattern (indicated by a continuous black line). As in the case of the Main Reef Leader (East Rand), three plots fall well outside the main concentration of points. The anomalous points in this and the Main Reef Leader (East Rand) will be discussed later. The average percentage of the heavy mineral components is :-

leucoxene	62.80%
zircon	32.95%
chromite	3.93%
	99.68%

Variations in the relative percentages are given as (i) including all samples, and as (ii) including only those samples occurring within the solid black line of Figure 6a :-

(i)		(ii)	
leucoxene	36.79%	leucoxene	21.16%
chromite	4.90%	chromite	6.17%
zircon	37.38%	zircon	15.45%

The effect of the three anomalous points on the percentage composition of the constituents is as marked as in the case of the Main Reef Leader (East Rand). To analyse these variations, two-component plots of all constituents were made. From these plots (Figures 6b, c, and d) it is seen that linear trends are again apparent. The same relationship between the relative percentages of the heavy minerals, as outlined for the Main Reef Leader (East Rand), appears to hold.

The three-component plot depicting the relative percentages of leucoxene, chromite, and zircon in the Main Reef is shown in Figure 7a. There is no marked concentration of the plots, as in the other two reefs, and the points tend to be scattered. The average content of the heavy minerals is as follows :-

leucoxene	54.90%
chromite	12.93%
zircon	31.70%
	99.63%

In order to amplify possible trends, two-component plots of all the minerals were made (Figures 7b, c, and d). No trends are apparent from these plots.

From the three-component plots (Figures 5a, 6a, and 7a) and the relative percentages of the heavy minerals given in Table III, it is seen that there are small, yet discernible, differences in the relative percentages of leucoxene, zircon, and chromite from reef to reef. The following table illustrates these differences :-

	% Heavy Mineral Constituents		
Reef	Leucoxene	Zircon	Chromite
Main Reef (West Wits Line, West Rand, Central Rand)	54.90	31.70	12.93
Main Reef Leader (Central Rand)	62.80	32.95	3.93
Main Reef Leader (East Rand)	66.72	18.78	14.46

Leucoxene is the dominant heavy mineral in all the reef horizons studied, and in all cases comprises over 50% of the total. It occurs very abundantly in the Main Reef Leader (East Rand), but, although conspicuous, least abundantly in the Main Reef. The leucoxene content of the Main Reef Leader (Central Rand) occupies an intermediate position. In all cases, zircon is dominant over chromite. The mineral is relatively abundant in the Main Reef and Main Reef Leader (Central Rand), where it occurs in about the same abundance. The zircon content of the Main Reef Leader (East Rand) is, however, lower than the zircon content in the other two horizons. Chromite is the least abundant of the heavy mineral constituents. It occurs relatively abundantly in the Main Reef Leader (East Rand), and in the Main Reef (especially of the West Wits Line), but is less important in the Main Reef Leader (Central Rand).

Although the source rocks which supplied sediments to the Witwatersrand basin during Upper Witwatersrand times must have been fairly similar, as evidenced by the nature of the conglomerates, differences probably existed over the large expanse of rock which must have given rise to these sediments. It is contended that the different relative percentages of leucoxene, chromite, and zircon, in the three reefs studied, are due to slightly different rock-types, or proportions of rock-types, in their respective source areas. This being the case, it would seem likely that the reef material composing each conglomerate horizon must have been derived from different source rocks, and that each reef is composed of material from one, or a number, of source areas. In the case of the Main Reef Leader (East Rand) and the Main Reef Leader (Central Rand), the relatively consistent grouping of the plots of heavy mineral percentages, except the three anomalous plots for both reefs, is of significance. These plots indicate that the reef material composing the Main Reef Leader (Central Rand) was probably derived from one entry point of reef material, and that the material composing the Main Reef Leader (East Rand) was also derived from one entry point, different to that of the former reef.

In the case of the Main Reef, however, the relatively large variation in the percentages is not in accordance with the consistent results obtained for the two reefs mentioned above. It is possible that these results reflect two or more different entry points of reef material. In Table III it is seen that the percentages for zircon and leucoxene in the Main Reef are fairly erratic, and no pattern which could indicate different entry points of reef material is apparent. The relative percentages of the chromite fraction in this reef are, however, of interest, and vary from place to place, as follows :-

Mineral	Average Percentage for entire Main Reef	Average Percentage for the West Wits Line	Percentage Difference
Leucoxene	54.900	50.952	3.948
Zircon	31.702	27.227	4.475
Chromite	12.932	21.760	8.828
	99.63	99.99	

It can be seen that the relative percentage of chromite, which for the entire Main Reef averages 12.932%, is 8.828% higher in the West Wits Line, where it averages 21.760%. The high percentage of chromite in these samples (i.e. from the Doornfontein, West Driefontein, Libanon, and Venterspost mines) is apparent, and possibly indicates that the Main Reef in the West Wits Line has been derived from a different source area to that of the Main Reef in the West Rand and Central Rand areas.

(c) Areal Variations in the Content of Heavy Mineral

The three anomalous plots of the relative percentages of heavy minerals from the Main Reef Leader (East Rand) and the Main Reef Leader (Central Rand) have still to be explained. The most significant feature of all the anomalous points is the fact that the samples they represent have been taken at depth from the Central Rand, or from the southeast portion of the East Rand, far removed from an assumed entry point of reef material. In all instances, the anomalous points are manifestations mainly of a decrease in the relative abundance of leucoxene and, to a lesser extent, chromite. Whether these erratic percentages are merely fortuitous, possibly due to sampling errors, is not known. It seems possible, however, in view of the location of the samples, that the results obtained may be the result of some process which became progressively more important away from an entry point of sedimentary material into a basin of deposition.

According to Van Andel (1959), four principal factors may modify the composition of a heavy mineral assemblage during transport :

(i) the weathering and elimination of certain unstable minerals in the source area, or in a depositional basin, could possibly be responsible for the modification of heavy mineral assemblages; the influence of the composition of sediments is negligible, however, in basins with a moderate to rapid rate of deposition;

(ii) the selective mechanical destruction of particular mineral components has often been cited as a possible cause for the modification of mineral assemblages; although data of this nature are few, downcurrent decreases in the percentage of such minerals as felspar have been reported; this decrease is presumably due to the differences in the susceptibility of various minerals to withstand wear; zircon, for example, because of its resistance to both chemical attack and abrasion, is, with repeated reworking, likely to increase, relative to other minerals;

(iii) the composition of the heavy mineral assemblage of a sediment is liable to modification by selective sorting, according to density and size, during transportation; many heavy minerals show a preference for specific size ranges which generally depend upon the particular size distribution of that mineral in the source rock; zircon, for example, is often preferentially concentrated in the smaller grades; abundant small zircon grains in a particular sedimentary rock should not be taken as an indication of source rock, rich in zircon, from which the particular sediment was derived; the effects of sorting can be pronounced when a heavy mineral assemblage contains species of widely divergent preferred ranges, and the influence of size is of more importance than density in sorting; and

(iv) post-depositional destruction of minerals, by what Pettijohn (1957) has called intrastratal solution, could possibly modify the heavy mineral assemblage of a sediment; however, it is doubtful whether this process could cause any differences in the relative percentages of heavy minerals over large areas.

In view of the fact that the Witwatersrand conglomerates were probably deposited fairly rapidly over a fairly short period of time, it seems unlikely that unstable constituents were eliminated by weathering in the depositional basin. The process of selective abrasion appears not to have brought about a change in heavy mineral composition, because most of the heavy minerals present are apparently capable of withstanding the same amount of abrasion. The influence of intrastratal solutions on the modification of heavy mineral constituents, although possibly effective on a minor scale, is probably of little importance on a large scale. It therefore seems likely that the observed downcurrent decrease in the relative percentage of leucoxene is due to selective sorting. As has been indicated by the size analyses carried out, the leucoxene fraction is always considerably larger than the accompanying chromite and zircon fractions, for a particular sample. If, as has been pointed out by Van Andel (1959), size is the most important prerequisite for selective sorting, then one would expect the larger mineral constituents, including leucoxene, to lag behind in a transporting current, and the finer differentiates of chromite and zircon, together with a relatively smaller proportion of leucoxene, to be transported further away from the source area. Although no quantitative data are available, abundant small grains of chromite and zircon (plus small grains of pyrite, leucoxene, and arsenopyrite) were observed in nearly every sample taken at a distance away from a postulated entry point of reef material. These minerals represent the fine-grained end-product of the sorting process, which is usually associated with a flood of small minerals. In support of this contention is the fact that the sorting coefficients of the heavy mineral constituents in these samples generally indicate good sorting, relative to samples taken closer to entry points. It is also possible that the effect of leucoxenic alteration of an original titanium-bearing mineral is greater in the case of smaller mineral grains. This being so, yellow leucoxenic rims surrounding chromite and zircon grains (common in samples of reef containing a flood of small heavy mineral components) could be the only manifestation of the original titanium-bearing mineral, and could afford an explanation for the decrease in the relative percentage of leucoxene. It should be borne in mind that well-preserved grains only were considered in this investigation.

D. SPHERICITY AND ROUNDNESS OF REEF CONSTITUENTS

(a) Sphericity

No special study of the shape or sphericity of mineral components was made. In the case of zircon grains, however, the ratio 1/b was measured, where 1 is the length and b is the breadth, as a rough estimation of sphericity. This method was adopted from Smithson (1939). The length to breadth ratios of the zircon distributions from seven sampling points in the Main Reef Leader (East Rand) were calculated. The results of this study, together with the median grain size of the distributions, are as follows :-

Sample Locality	Median grain size	Length : breadth Ratio
Vlakfontein	.288	2 : 1.27
S.A. Lands	.286	2 : 1.29
Spaarwater	.259	2 : 1.30
Sub Nigel	.230	2 : 1.29
Grootvlei	.227	2 : 1.37
Marievale	.178	2 : 1.35
East Daggafontein	.160	2 : 1.31

The ratio of 1/b remains relatively constant, and the average ratio is 2 : 1.32 or 1 : .66. Of interest is the fact that the ratio tends to become smaller as the grain size becomes smaller.

It has commonly been observed that detrital grains of zircon are often elongated in one direction, giving a characteristic shape known as a roller. This shape is produced as a direct result of the prismatic nature of the mineral. Although, as pointed out by Smithson (1939) and others, the length to breadth ratio of primary zircons occurring, say, in a granitic rock, is variable, there is a definite tendency for this ratio to change as a result of sedimentary transport. Transportation has the effect of wearing down, or breaking off, the pyramidal terminations of euhedral grains, so that the length of a particular grain decreases more rapidly than the width. Thus, large elongated zircon grains, for the most part having well-preserved pyramidal terminations, would be expected near a source of primary grains. With sedimentary transport, some of the pyramidal terminations would become rounded to a varying degree, while others would succumb to fracturing. The nett effect would be a crop of fairly well-rounded zircon grains with a decrease in the length to breadth ratio. With more rigorous conditions of transportation, or with repeated reworking, most of the pyramidal terminations might be broken from the parent grain, which, in turn, would become very well rounded and oval to spherical in shape. This would result in a final product of well-rounded, roughly spherical grains, possibly mixed with small angular fragments produced as a result of fracturing just prior to deposition. The ratio of the length to breadth of zircon grains in such cases would approach unity.

The slight change in the length to breadth ratio of the zircons, with decreasing grain size, or with increasing distance from source, is attributed to size-reducing processes similar to those outlined above. It might be expected that the zircon grains near the postulated points of entry of reef material would be more euhedral in shape, if they had been derived from a nearby primary source. The generally rounded nature of these grains, however, suggests that they underwent a considerable amount of abrasion in a river system prior to their deposition in the basin, where further transporting agencies were responsible for the small observed decrease in the length to breadth ratio. Another possibility is that the zircon grains resulted from the reworking of an earlier deposit within the same depositional basin. Whichever process was responsible, it seems likely that the detrital zircon grains, as they occur in the matrix of the Main Reef Leader (East Rand), have undergone two cycles of transportation or sedimentary reworking. The shape of the grains occurring in the matrix of the Main Reef and Main Reef Leader (Central Rand) suggests that they have had a similar history to the zircon grains in the Main Reef Leader (East Rand).

(b) Roundness

No special study of the roundness of heavy mineral components was made, because it is questionable if reliable quantitative results are obtainable from a roughly polished two-dimensional surface. In the Ultrapak investigation, for example, grain boundaries were not always sharply defined. In general, however, there appears to be a slight increase in the degree of rounding away from postulated source areas. Visual inspection of Figure 12 indicates that the smaller zircon grains generally exhibit better-rounded edges than the larger grains.

E. THE GRAIN-SIZE OF THE MINERAL COMPONENTS

(a) The Size Frequency Distributions

The median grain-sizes of zircon, chromite, leucoxene, pyrite, and quartz were calculated from cumulative curves for most of the samples studied. In addition, the average grain-size of not less than ten arsenopyrite-glaucodot grains were calculated for each of a number of samples of the Main Reef Leader (East Rand), where the minerals occurred in sufficient quantity. Sample localities are shown on Figure 1, indicating the mine boundaries on the Central Rand, East Rand, West Rand, and West Wits Line. Separate maps were drawn to represent the lateral size distribution of individual mineral species (see Figures 8, 9, 11, 13, and 14). Median grain-sizes of the particular mineral under investigation are plotted on the maps, and isopleths, or lines joining points of equal size, are depicted. The limited number of sample localities in some areas made the drawing of isopleths difficult. Where it was possible to draw contours with confidence, continuous dark lines are shown. Where the position of contours is uncertain, due to a limited amount of data, broken lines appear. The Main Reef Leader (East Rand) and the Main Reef Leader (Central Rand) are covered by a fair number of points. Sample localities on the Main Reef, however, are very dispersed, and for this reason no isopleths were drawn for this reef.

Statistical parameters for particular minerals in particular reef horizons are not given in Table IV if there were insufficient grains present for a statistical analysis, or if grains were totally unsuitable for such an analysis. For example, some sections examined contain crystalline pyrite only, and no size measurements could be made on rounded pyrite. Sizes are in millimetres.

TABLE IV : STATISTICAL PARAMETERS OF HEAVY MINERAL, SULPHIDE, AND QUARTZ DISTRIBUTIONS

(i) Zircon

Main Reef Leader (East Rand)

Locality and Sample	Median Md	Third Qt. Q 3	First Qt. Q 1	Sort. Coeff. So	Skewness Sk
Geduld	.291	.414	.208	1.410	1.028
Vlakfontein	.288	.405	.200	1.420	.985
S.A. Lands	.286	.395	.202	1.390	.966
Daggafontein	.281	.360	.214	1.290	.974
East Geduld	.263	.361	.216	1.290	1.122
Spaarwater	.259	.354	.189	1.360	1.000
Van Dyk	.248	.333	.199	1.290	1.070
Sub Nigel	.230	.315	.165	1.370	.987
Grootvlei	.227	.300	.184	1.270	1.070
Modder East k4702-k4707	.220	.300	.168	1.330	1.640
Modder East k4710-k4714	.215	.271	.153	1.330	.900

Main Reef (West Wits Line, West Rand, Central Rand)

Libanon	.300	.372	.238	1.250	.985
C.M.R.	.272	.333	.227	1.208	1.030
Venterspost	.261	.345	.205	1.299	1.040
West Driefontein	.226	.265	.182	1.207	.945
Doornfontein	.148	.201	.111	1.345	.790

(iii) Leucoxene

Main Reef Leader (East Rand)

Geduld	.398	.464	.303	1.238	.898
Daggafontein	.396	.508	.299	1.310	.965
S.A. Lands	.390	.498	.300	1.289	.980
Vlakfontein	.380	.470	.296	1.261	.965
East Geduld	.376	.467	.294	1.261	.970
Grootvlei	.355	.460	.280	1.282	1.020
Van Dyk	.344	.425	.271	1.252	.970
Sub Nigel	.311	.398	.240	1.280	.990
Modder East k4710-k4714	.299	.405	.236	1.313	1.060
Modder East k4702-k4707	.280	.383	.213	1.340	1.040
Marievale	.270	.347	.211	1.282	1.000
Vogelstruisbult (total)	.262	.370	.202	1.353	1.080

Main Reef Leader (Central Rand)

Crown Mines 8	.405	.498	.310	1.270	.940
E.R.P.M. 2 (90 grains)	.403	.486	.313	1.246	.935
E.R.P.M. 2 (180 grains)	.400	.479	.308	1.267	.920
Crown Mines 5	.398	.481	.308	1.270	.950
Rose Deep	.395	.494	.291	1.305	.920
C.M.R.	.385	.473	.315	1.227	1.000
E.R.P.M. 9	.385	.465	.305	1.235	.960
Crown Mines 7	.310	.428	.247	1.318	1.100
Crown Mines 6	.298	.396	.236	1.297	1.050
City Deep	.210	.248	.160	1.249	.900

(iv) Pyrite

Main Reef Leader (East Rand)

S.A. Lands	.305	.395	.237	1.291	1.000
East Geduld	.298	.386	.224	1.312	.980
Daggafontein	.296	.400	.227	1.328	1.040
Modder East k4701-k4707	.280	.370	.216	1.310	1.050
Grootvlei	.272	.362	.206	1.326	1.000
Sub Nigel	.261	.339	.197	1.313	.980

Vogelstruisbult (400 grains)	.189	.248	.143	1.310	.998
Vogelstruisbult (100 grains)	.183	.238	.138	1.310	.985
Marievale	.178	.227	.144	1.250	1.030
East Daggafontein	.160	.212	.125	1.300	1.030
Geduld (zircons in footwall)	.117	.138	.085	1.270	-

Main Reef Leader (Central Rand)

Crown Mines 5	.312	.429	.211	1.420	.909
C.M.R.	.286	.385	.213	1.340	1.040
Crown Mines 8	.262	.361	.197	1.350	1.030
E.R.P.M. (250 grains)	.262	.354	.206	1.300	1.060
E.R.P.M. (75 grains)	.269	.368	.218	1.290	1.110
Rose Deep	.260	.371	.184	1.420	1.000
E.R.P.M. 9	.253	.335	.214	1.240	1.120
Crown Mines 7	.225	.275	.195	1.180	1.050
Crown Mines 6	.211	.305	.219	1.170	1.490
City Deep	.205	.240	.157	1.230	.940

Main Reef (West Wits Line, West Rand, Central Rand)

C.M.R.	.318	.426	.238	1.340	1.000
Venterspost	.296	.406	.213	1.380	.990
Libanon	.282	.394	.200	1.404	1.280
City Deep	.251	.332	.187	1.335	.985
E.R.P.M.	.243	.329	.175	1.370	.975
Luipaardsvlei	.223	.315	.164	1.388	1.040
West Driefontein	.217	.270	.168	1.269	.965
Durban Deep	.212	.314	.150	1.450	1.040
Rose Deep	.211	.273	.160	1.307	.985
West Rand Cons.	.198	.248	.155	1.264	.980
Doornfontein	.188	.243	.148	1.282	1.020

(ii) Chromite

Main Reef Leader (East Rand)

East Geduld	.278	.347	.222	1.251	1.060
Geduld	.278	.373	.223	1.296	1.065
Daggafontein	.262	.325	.214	1.234	1.010
S.A. Lands	.261	.345	.216	1.266	1.090
Grootvlei	.249	.307	.195	1.255	.965
Vlakfontein	.235	.306	.182	1.300	1.010
Modder East k4710-k4714	.224	.300	.160	1.370	.960
Modder East k4702-k4707	.221	.264	.180	1.212	.975
Spaarwater	.215	.262	.174	1.229	.985
Sub Nigel	.193	.259	.152	1.308	1.060
Vogelstruisbult (250 grains)	.173	.210	.139	1.230	.975
Vogelstruisbult (100 grains)	.167	.213	.138	1.244	1.050
East Daggafontein	.165	.200	.132	1.231	.970
Marievale	.161	.201	.129	1.250	1.000

Spaarwater	.213	.272	.163	1.291	.975
Vogelstruisbult	.199	.245	.155	1.257	.960
East Daggafontein	.190	.259	.153	1.301	1.090
Marievale	.188	.241	.160	1.227	1.090

Main Reef (West Wits Line, West Rand, Central Rand)

Venterspost	.359	.443	.289	1.218	.990
Libanon	.334	.401	.258	1.245	.930
E.R.P.M.	.310	.410	.231	1.333	.985
West Rand Cons.	.297	.372	.229	1.273	.965
C.M.R.	.287	.377	.226	1.292	1.030
Luipaardsvlei	.258	.315	.192	1.280	.905
Doornfontein	.240	.330	.178	1.360	1.020
Rose Deep	.238	.307	.183	1.294	.990
West Driefontein	.237	.291	.198	1.212	1.020
Durban Deep	.235	.310	.176	1.327	.985

(v) Quartz

Main Reef Leader (East Rand)

Vlakfontein	.770	.980	.572	1.315	.945
Geduld	.762	1.020	.582	1.320	1.020
S.A. Lands	.740	1.120	.520	1.460	1.070
Modder East k4701-k4707	.610	.874	.404	1.490	.948
Vogelstruisbult	.548	.707	.426	1.250	1.003
East Daggafontein	.540	.730	.387	1.370	.969
East Geduld	.530	.725	.380	1.380	.982
Marievale	.520	.788	.345	1.510	1.000
Grootvlei	.471	.700	.341	1.430	1.070
Sub Nigel	.457	.658	.308	1.460	.971
Modder East k4710-k4714	.452	.602	.346	1.310	1.010
Spaarwater	.405	.610	.270	1.505	1.000

Main Reef Leader (Central Rand)

Crown Mines 8	.740	.970	.485	1.425	.870
Crown Mines 5	.630	.870	.429	1.425	.941
Crown Mines 7	.600	.900	.416	1.470	1.040
C.M.R.	.510	.638	.370	1.310	.907
Crown Mines 6	.440	.640	.315	1.425	1.040
E.R.P.M. 11	.370	.490	.275	1.335	.985

Main Reef (West Wits Line, West Rand, Central Rand)

West Driefontein	.950	1.300	.754	1.310	1.080
Durban Deep	.858	1.270	.670	1.260	1.150
C.M.R.	.810	1.100	.622	1.320	1.030
City Deep	.800	1.090	.575	1.370	.977
Rose Deep	.760	1.000	.555	1.340	.961
Venterspost	.750	.975	.550	1.330	.953
West Rand Cons.	.745	1.050	.541	1.390	1.020
Doornfontein	.740	.970	.568	1.300	1.010
E.R.P.M.	.600	.850	.395	1.460	.932
Luipaardsvlei	.572	.750	.411	1.350	.941
Libanon	.530	.692	.397	1.320	.970

(vi) Arsenopyrite (Plus Glaucodot and Cobaltite)

(N.B.) In most cases insufficient grains were present for the construction of cumulative curves, and the figures given represent the average of 10 grains).

Main Reef Leader (East Rand)

Sample	Average grain size in mm.
Geduld	.152
S.A. Lands	.150
Modder East k4701-k4707	.150
Vlakfontein	.140
East Geduld	.130
Modder East k4710-l4714	.128
Grootvlei	.122
Marievale	.120
Sub Nigel	.119
Spaarwater	.112

(b) Areal Variations in Grain-Sizes

(i) Main Reef Leader (East Rand)

Isopleth maps representing the lateral size variation of zircon, chromite, leucoxene, pyrite, arsenopyrite, and quartz grains are shown in Figures 8 and 9. The contours are based on 14 sample localities in the case of zircon, 13 in the case of chromite, 12 in the case of leucoxene, 10 in the case of pyrite, 10 in the case of arsenopyrite, and 12 in the case of quartz grains. All the isopleths, excepting those of quartz, have been drawn at .02 mm. intervals. To arrive at this value, a number of check measurements were made. These measurements are shown in the following table, which indicates the variations in statistical parameters obtained by measuring a large number of grains and a small number of grains, respectively, in the same sample :-

Sample Locality	Mineral Species	Number of grains measured	Md mm.	Q3	Q1	Differences between Md's
Vogelstruisbult	Zircon	400	.189	.248	.143	.006
		100	.183	.238	.138	
Crown Mines	Zircon	250	.262	.354	.206	.007
		75	.269	.368	.218	
Vogelstruisbult	Chromite	250	.173	.210	.139	.006
		100	.167	.213	.138	
E.R.P.M.	Leucoxene	180	.400	.479	.308	.003
		90	.403	.486	.313	

The maximum difference (or error) as can be seen is .007 mm. In order to fix a value on either side of the median grain-size, the above value was doubled, giving a value of .014 mm. To cover this error, a contour interval of .02 mm. was chosen. In the case of quartz, a contour interval of .05 mm. was necessary to avoid crowding. It should be stressed here that the local variations could not be determined in mineral size over a few thousand feet between individual sample localities shown on the map (Figure 1). It is, however, important to know this "within" variation in mineral size, to give maximum confidence to the isopleth patterns obtained. In support of the contention that mineral size does not vary substantially over a distance of up to 100 feet from a particular sample locality, is the fact that where 4 or 5 samples were taken over 10 to 100 feet of reef, it was found that the median grain-sizes of the heavy mineral distributions remained similar in all samples.

From Figures 8 and 9, it can be seen that the pattern which emerges is a fairly symmetrical one, with a general grain-size decrease from the northwest-central portion of the basin radiating outwards in southerly, westerly, and easterly directions. The largest grains occur in the following mines : New Kleinfontein, Government Areas, Brakpan, Geduld, East Geduld, Springs, S.A. Lands, Daggafontein, and Vlakfontein. The smallest grains occur at Grootvlei, East Daggafontein, Vogelstruisbult, Marievale, and Spaarwater mines, occupying positions on the perimeter of the basin. Isopleths depicting the smallest and largest grains of zircon, chromite, and pyrite occupy very similar positions. The isopleth pattern of the arsenopyrite distribution should not be compared with those of the other minerals, because the sizes are based on the average size of the grains, and not on the median grain-size, as is the case with the other constituents. The contours for all the minerals, excepting arsenopyrite and quartz, show a flatter gradient between the northern portion of Vlakfontein and the southern portion of Spaarwater, in contrast to the steeper gradient of contours between Daggafontein and the eastern portion of East Daggafontein.

Marshall (1927), quoted by Pettijohn (1957), attributed size decrease, especially if there is a large disparity in the sizes of clastic elements, such as in the case of a conglomerate, to processes such as impact and grinding. A number of workers have shown that the abrasion process is markedly more effective in the case of pebbles than in the case of sand-size material. Observations on the downcurrent increase in the degree of rounding of sand grains (which would indicate attrition or abrasion) are, however, conflicting. Plumley (1948) indicated a downstream increase in the degree of rounding in a stream carrying clastic particles of variable size. Russel and Taylor (1937), on the other hand, showed that there is a downstream decrease in the amount of rounding of sand particles in the Mississippi River. They attributed this to fracturing. Laboratory and field observations have shown that abrasion is generally ineffective in producing the observed downstream decrease in size, in the sand grade at least. According to Pettijohn (1957), progressive sorting of the clastic particles in a stream is the main reason for the commonly observed downstream decrease in grain-size. Causes of such progressive sorting have been attributed to a progressive decrease in the competence of the transporting agent, and a lagging behind of the larger particles because of fluctuations in competency. Decrease in gradient, and deposition induced by an aggrading current can produce a marked downcurrent sorting.

From the isopleth maps, it would seem likely that the observed decrease in the size of heavy mineral constituents away from the northwest corner of the East Rand is due to the progressive sorting action produced by some type of aggrading current. The fan-like distribution of all the isopleths indicates that a large river must have debouched into a basin, lake, or deltaic flat, in the area north of Benoni. The various clastic constituents were spread out in a fan-like fashion, with decrease in grain-size in an easterly to southerly direction. The direction of current flow can roughly be sketched on to the maps by drawing normals to the isopleths. The pattern formed by such lines is similar for every mineral constituent. Thus, it would appear likely that all the reef material composing the Main Reef Leader (East Rand) was transported from a relatively narrow zone, or entry point, somewhere north of Benoni.

Mellor (1915) noted that the most interesting feature of the Main Reef Leader (East Rand) was the marked parallelism of elongated patches, or payshoots, of reef with high gold values. These patches represent portions of reef distinguished by a greater thickness of conglomerate and larger average size of pebbles, invariably accompanied by good gold values. He noted that there was a marked parallelism of stoped areas in the Nigel and Brakpan mines, striking from N.N.W. to S.S.E. Reinecke (1927) and Bridges (1942), quoted by du Toit (1957), added to the picture of the payshoot pattern in the East Rand. Figure 10a, from du Toit (1957), shows the positions and directions of the payshoots in the Main Reef Leader of the East Rand. The pattern is one of a braided, fan-shaped arrangement of shoots, radiating towards the east, southeast, and south, from a locus to the northwest of Benoni. According to Reinecke (1927), these shoots represent the courses of transporting currents. Normals drawn to the isopleths for the heavy mineral distributions, theoretically indicating the approximate direction of current transport, give a pattern which is generally similar to the payshoot pattern shown in Figure 10a.

In addition to a general thinning of stratigraphic units, as a whole, from north-west to southeast, there is a falling off in the robustness of the reef in this direction. According to Reinecke (1927), the reef zone consists of conglomerates and intercalated quartzites which may, in the Benoni area, be up to 400 feet thick. In the vicinity of New Kleinfontein, New Modder, Modder Deep, and Van Ryn Deep, all situated at the north-east portion of the East Rand, up to fifteen reefs have been mined in the Main Reef zone. Eastwards, the zone thins to a width of 6 to 10 feet, and further east and southeast, diminishes steadily, but not as rapidly. Mellor (1915) noted a change in the robustness of the actual payshoots, from the New Kleinfontein area, where the reef is very robust and pebbles large, to the Nigel area where patches of thinner and smaller pebbled conglomerate occur. In the northwestern part of the East Rand, areas intermediate to the payshoots are occupied by reef which, although not as good as the reef within the payshoots, is nevertheless of economic importance. In the southeastern part of the basin, where the payshoots fan out, areas intermediate to the shoots contain no reef development, and the quartzites which normally form the hangingwall of the reef lie directly on the footwall Jeppestown shale. This stratigraphic evidence strongly points to the possibility of there being an entry point of reef material in the area of the New Kleinfontein mine, i.e. in the Benoni area.

Cross-bedding has the useful property, if sufficient measurements are taken and treated statistically, of indicating current directions, and the direction of movement of sedimentary material. Hargraves (1961) reported the results of a reconnaissance study of cross-bedding in Main-Bird quartzites from the East Rand. The pattern obtained indicates a consistent southerly and southeasterly direction of sediment transport (see Figure 10b). Assuming that the reef material was transported in the same direction as the associated arenaceous horizons, then an entry point of material north-west of Benoni is again indicated. In addition, there is a decrease in the average thickness of cross-bedded units to the south and southeast, which is the direction of transport indicated by cross-bedding.

(ii) Main Reef Leader (Central Rand)

Isopleth maps representing the areal median size variation of zircon, leucoxene, and quartz grain distributions are shown in Figure 11. The contours are based on 9 sample localities in the case of zircon, 9 in the case of leucoxene, and 5 in the case of quartz. All the isopleths, excepting those of quartz, have been drawn at .02 mm. intervals. In the case of the latter mineral a contour interval of .05 mm. was used. It should be borne in mind from the outset that these isopleths have been drawn merely to give a general appraisal of the size variations of the minerals mentioned above, taking into account the limited number of sampling points on which the isopleths are based.

It can be seen that there is a fairly large variation in the sizes of the minerals under investigation. The pattern which emerges, although being similar to the isopleth patterns of the Main Reef Leader (East Rand), as far as the similarities between the individual mineral species are concerned, is somewhat different to the pattern in the latter reef, due to the fact that the isopleths run roughly parallel to the strike of the reef. Two major inflections are, however, apparent. These inflections are due to relatively large grains of zircon, leucoxene, and quartz occurring in the northern portions of Crown Mines and C.M.R., and to relatively large grains of zircon and quartz in the southern portion of E.R.P.M. Adjacent to these two inflections are two areas, in the vicinity of the City Deep and Simmer and Jack mines, and in the vicinity of the Rand Leases and Durban Deep mines, which contain relatively small mineral constituents. Besides the inflections, one of the most significant features of the isopleths is the steep gradient of mineral grain-size decrease, generally from north to south.

In order to illustrate visually the type of size difference between a distribution of large grains and a distribution of smaller grains, 72 consecutively measured zircon grains are depicted in Figure 12. These grains, which were measured by means of Ultrapak illumination, have been drawn to scale, using a camera lucida microscope attachment. Figure 12a shows 36 zircon grains from the Main Reef Leader at Crown Mines. The sample, from which the measurements were made, was taken from reef in the northern section of the mine at a depth of 3,180 feet. The median grain-size of the zircons occurring in this area is .312 mm. Figure 12b shows 36 zircon grains, also from the Main Reef Leader at Crown Mines, where the measurements were made from a sample of reef taken near the southern boundary of the mine at a depth of 9,110 feet. The median grain-size of the zircons occurring in this part of the reef is .211 mm. The disparity in grain-size, indicated by the isopleths, of these two distributions is at once apparent. If the average dip of the Main Reef Leader in the Crown Mines area is taken as 40° south, then it is possible to calculate the rate of size decrease of heavy mineral grains. Thus, in the area under consideration the median grain-size of the zircon distribution changes by .101 mm. over a distance of 9,226 feet or about 1.75 miles.

Although no statistical work on pebble sizes was undertaken because of the limited surface area of the samples under investigation, visual comparison suggests that in some cases, at least, there is a striking relationship between the size of pebbles and the size of heavy mineral constituents. In the samples mentioned above, the larger zircon grains are associated with larger pebbles.

Insufficient grains of chromite, arsenopyrite, and pyrite were present in the samples of Main Reef Leader (Central Rand) for a statistical appraisal. The isopleth pattern for quartz grain size-distribution, although similar to the patterns obtained for zircon and leucoxene, is probably less trustworthy.

Areal size variation of the mineral components of the Main Reef Leader are attributed to the same, or similar, features which brought about variation in mineral size in the Main Reef Leader (East Rand). It is concluded, from the isopleth patterns, that the material composing the Main Reef Leader, was derived from at least one point of entry of reef material. A probable point of entry was present to the northwest of the present Crown Mines. As in the case of the Main Reef Leader (East Rand), it appears as though the direction of transport was from northwest to southeast. Little published data exists on the extent and persistence of payshoots in the Main Reef Leader of the Central Rand. Where these features do occur, their presence is somewhat masked due to the fact that the whole reef is payable, and the shoots cannot be traced by the stoping patterns, as is the case with the payshoots in the Main Reef Leader (East Rand). Reinecke (1927) divided the payshoots in the Main Reef Leader of the Central Rand into two types : (i) those in which the paystreak is defined by a narrow reef with large pebbles, and is bordered by bands with no pebbles at all, or by grits, and (ii) those in which values are more evenly distributed over a greater reef width. In general, the axes of the payshoots tend to form a braided pattern, with high-value zones trending between northwest and southwest. In a few cases, payshoots were found trending north-south. There are indications in the Crown Mines area that the original transporting currents flowed westwards during the time of deposition of reef material. From the above evidence, it seems likely that depositing currents flowed in a number of directions from between northwest and northeast, if the payshoots represent the direction of current flow.

(iii) Main Reef

The limited number of samples available from the Main Reef over an extensive strike distance precluded the possibility of constructing isopleth maps with confidence. In addition, the presence of a number of large faults such as the Bank, Venterspost, West Rand, Witpoortje, and Roodepoort faults, would have an effect on the isopleth patterns.

Values obtained for the size of zircon, chromite, and quartz grains are given in Figure 13. The most significant feature of these values is the fact that the grain-sizes of the component minerals appear to be smaller in a down-dip direction. In the Western Deep Levels, West Driefontein, Blyvooruitzicht, and Doornfontein mines, grain-sizes appear to decrease from N.N.E. to S.S.W., whereas in the Western Areas, Venterspost, and Libanon mines, grain-size decrease appears to be from N.W. to S.E. In the Randfontein, West Rand Consolidated, and Luipaardsvlei mines, isopleths would appear to conform roughly to the reef outcrop pattern, and grain-size generally appears to decrease from N.N.W. to S.S.E. The pattern of grain-size decrease of mineral species in the Main Reef in the Central Rand is similar to the pattern obtained for the same minerals in the Main Reef Leader in this area. There appears to be a tendency for grain-size to decrease roughly in a north to south direction, and large mineral grains again seem to be characteristic of the northern portions of C.M.R. and Crown Mines. In the E.R.P.M. - Rose Deep area, it would appear as if grain-size decreases from N.N.E. to S.S.W.

The causes of the size reduction of the mineral components of the Main Reef are attributed to the same processes that have been outlined earlier, i.e. mainly selective sorting taking place in an aggrading current from a point of entry. The reef in the Western Deep Levels, West Driefontein, Blyvooruitzicht, and Doornfontein mines has been derived from a source area to the north or north-northeast. This source area was probably similar, and related to, the source area which gave rise to the reef in the Western Areas, Venterspost, and Libanon mines. This is in accord with the relative percentages of heavy minerals described earlier. The relative abundance of chromite is characteristic of the Main Reef in this area. The reef in the so-called West Rand Syncline, in Randfontein Estates, West Rand Consolidated, and Luipaardsvlei mines, was derived from a source area lying N.N.W. of the present mining area. This is in accord with the relative decrease in the amount of chloritoid in the matrix of the Main Reef from this area. In the area between the Durban Roodepoort Deep and City Deep mines, material composing the reef has been derived from a source approximately to the northwest. As in the case of the Main Reef Leader, payshoots are not readily definable in the Main Reef. Areas of greater payability than the normal tenor of gold values are, however, present. In the Crown Mines area, for example, payshoots have been reported as trending from north to south. Payshoots are fairly well developed in the Main Reef of the West Rand Consolidated area, and apparently trend from N.N.W. to S.S.E. These features substantiate the possibility of there being an entry point of Main Reef material northwest of Krugersdorp, and indicate the possibility of there having been north-south flowing currents in the Central Rand area. Recent work on cross-bedding directions in the Main-Bird Series of the West Rand syncline (Steyn, 1963) on the West Rand Consolidated, Randfontein Estates, and Luipaardsvlei mines has indicated a current direction from approximately N.W. to S.E. Indications are that, for the Livingstone Reef at least, an entry point of reef material existed somewhere to the northwest of the present outcrop.

F. THE DEGREE OF SORTING OF THE REEF CONSTITUENTS

(a) The Values Obtained

The sorting coefficient, as defined by Trask (1932), quoted by Pettijohn (1957), is essentially a measure of the grain-size distribution, and can only be used to advantage when sediments have a normal distribution and are well-sorted (Sharp and Pow-Foong Fan, 1963; Friedman, 1962). In general, it can be said that sorting is one of the most useful attributes of a sediment, and usually gives a good indication of the environment under which a particular sedimentary rock was deposited.

The sorting coefficients of all the mineral constituents measured are given in Table IV. In addition, the sorting values of zircon, chromite, and leucoxene distributions from the Main Reef Leader (East Rand), according to the inclusive graphic standard deviation method (Folk, 1961) have been calculated.

(b) The Trask Sorting Coefficients

Zircon is, relative to the others, the most poorly sorted heavy mineral constituent, and it is thought that this is mainly due to the method of grain measurement, i.e. the maximum horizontal intercept. The prismatic nature of the grains emphasizes the disparity in size between the largest and smallest individuals. In general, however, zircon grains are well sorted, the sorting coefficients varying from 1.17 to 1.45, with an average of 1.30. The sorting coefficients tend to be erratic, but there is a definite relation between this measure and grain-size. In general, it can be said that the larger the median grain-size of a particular distribution, the poorer will be the sorting of that distribution. This relationship can be seen in Figures 12a and b. In Figure 12a, the median grain-size of the zircon distribution is .312 mm., with a corresponding sorting coefficient of 1.42. In Figure 12b the median grain-size is .211 mm., with a corresponding sorting coefficient of 1.17 mm. Further proof of the above-mentioned relationship is afforded by contours representing the areal variation in sorting of zircon distributions in the Main Reef Leader (East Rand). These contours (see Figure 14a), which are based on 13 sampling localities, give a very similar pattern to the isopleth pattern of grain size of zircon in the same reef. The contours, which are drawn on the basis of a contour interval of .05, display a flatter gradient between the Vlakfontein Mine and the southern portion of the Spaarwater and Sub Nigel mines. Zircon distributions from the Modderfontein, Government Areas, Geduld, New State Areas, Daggafontein, Springs, Brakpan, Van Ryn Deep, and Modder Deep mines, which generally contain large heavy mineral constituents, are characterized by relatively poor sorting coefficients, while zircon distributions from the Grootvlei, East Daggafontein, Vogelstruisbult, Marievale, Nigel, Spaarwater, and Van Dyk mines, which generally contain small heavy mineral constituents, are marked by relatively good sorting coefficients.

Chromite distributions generally tend to have better sorting coefficients than accompanying zircon distributions. This is probably due to the fact that detrital grains are spherical rather than oval or elongated, as is the case with zircon grains. Sorting coefficients vary between 1.212 and 1.345, with an average of about 1.250. Coefficients tend to be erratic, but there is again a definite relationship between size and sorting. This is illustrated in Figure 14b where contours (based on 12 sampling points), representing the areal variation in the degree of sorting of chromite distributions in the Main Reef Leader (East Rand) are depicted. The pattern obtained is essentially similar to the isopleth pattern for the grain-size of chromite in the same reef. The large median grain-size of chromite in the northeastern portion of the basin corresponds to relatively poor sorting of this mineral, whereas chromite distributions around the outer margin of the basin are characterized by relatively good sorting.

The sorting coefficients of leucoxene distributions are generally slightly higher, i.e. the sorting is slightly poorer, than those of chromite, but not as high as those of zircon. Coefficients of sorting vary between 1.227 and 1.340, with an average of approximately 1.280. As in the case of the zircon and chromite distributions, there is a definite relationship between size and sorting. This is illustrated in Figure 14c, which is a contour map showing the areal variation in the sorting of leucoxene distributions in the Main Reef Leader (East Rand).

Rounded pyrite grains generally tend to have similar sorting characteristics to chromite and leucoxene distributions. Sorting coefficients vary from 1.212 to 1.360, with an average of about 1.300. There again appears to be a relationship between grain-size and sorting, but no contours were drawn because of the lack of data. Insufficient grains of arsenopyrite were present for a statistical study, and no sorting coefficients for this mineral were calculated.

In general, the sorting coefficients of quartz grains are higher than those of the heavy minerals. Good sorting is, however, still indicated. Values for the sorting of quartz distributions vary from 1.25 to 1.51, with an average of about 1.36. It is not apparent whether there is any marked relationship between grain-size and the degree of sorting. It seems likely, due to the difficulty of measuring the entire quartz distribution, that results obtained are liable to be untrustworthy. No contours were drawn.

The upper class limits of 2.5 for well-sorted sediments and 4.5 for normally-sorted sediments, obtained by Trask (1932), quoted by Pettijohn (1957), appear to be too high for sandstones. This shortcoming of the Trask values has been noted by various workers who, still using Trask's formula for obtaining sorting coefficients, have proposed class limits more in accord with observed sorting characteristics. Table V (after Friedman, 1962) summarizes and compares various sorting classifications based on Trask's sorting coefficient. Table VI presents the results of the present investigations.

TABLE V : SORTING CLASSES BASED ON TRASK'S SORTING COEFFICIENT (So)
(from Friedman, 1962, p.739)

	Sorting Classes	Designation of Sorting
Trask (1932)	1.0 - 2.5	well sorted
	2.5 - 4.5	normally sorted
	> 4.5	poorly sorted
Schneiderhoehn (1953)	1.0 - 1.23	almost perfectly sorted
	1.23 - 1.32	excellently sorted
	1.32 - 1.41	very well sorted
	1.41 - 1.51	well sorted
	1.51 - 1.74	moderately sorted
	1.74 - 1.87	deficiently sorted
	1.87 - 2.00	poorly sorted
	> 2.00	very poorly sorted
Folk (1954), after Fuechtbauer (1959)	1.0 - 1.16	very well sorted
	1.16 - 1.26	well sorted
	1.26 - 1.60	moderately sorted
	1.60 - 2.63	poorly sorted
Fuechtbauer (1959)	1.0 - 1.23	very well sorted
	1.23 - 1,41	well sorted
	1.41 - 1.74	moderately sorted

TABLE VI : SORTING COEFFICIENTS OF MINERALS IN MAIN REEF AND MAIN REEF LEADER

Mineral	Range in Sorting Coefficients	Average Sorting Coefficient
Zircon	1.170 - 1.450	1.30
Chromite	1.212 - 1.345	1.25
Leucoxene	1.227 - 1.340	1.28
Pyrite	1.212 - 1.360	1.30
Quartz	1.250 - 1.510	1.36

Comparison of the results obtained in the present investigation with the values given above, indicate that the mineral constituents under investigation vary from excellently sorted to moderately sorted. According to Trask (1932), all the constituents can be classed as well-sorted.

The environmental significance of sorting has been discussed by Friedman (1962), on the basis of the standard deviation method of calculating this property. It is feasible, by means of a table (Friedman, 1962, p. 752), to convert Trask sorting values to the standard deviation classification. It is then possible, from the standard deviation classification, to allocate sediments to particular environments deduced from a genetic sorting classification drawn up by Friedman (1962, p. 750) after a study of the sorting characteristics of approximately six hundred recent sand samples from known environments. It is emphasized that the classification is for use with sands and sandstones only, but since only the sand grade fraction of the matrix is under discussion, it was felt that use of the classification was warranted. According to the classification, sorting coefficients between 1.17 and 1.20 indicate an environment of deposition characteristic of most beach sands, many or most marine sands above wave base, and some river sands. It is apparent from Table IV that only a small percentage of sorting coefficients obtained fall into this group. Sorting values, falling within the next group (between 1.20 and 1.35) indicate an environment of deposition characteristic of most river sands and many beach sands. The majority of sorting coefficients obtained fall in this range. Sorting coefficient values between 1.35 and 1.87 (the next group), indicate an environment of deposition characteristic of many river sands, and some continental shelf sands, below wave base. From the sorting coefficients obtained in the present investigation, it is apparent that very few of the sorting coefficients of heavy minerals fall in this group. Fifty percent, or more, of the sorting coefficients of quartz within the sand fraction, however, fail into this group. It is thought that the relatively poorer sorting of the quartz grains within the matrix is probably a direct result of the size of this mineral constituent. Friedman (1962) came to the conclusion that coarse-grained sediments, and particularly those with a mean grain-size of more than .500 mm., are more poorly sorted than medium- to fine-grained sands (corresponding approximately to the size of heavy mineral constituents in the banket), from the same environment. In the present study, the average size of quartz grains in the sand grade, was found to be slightly more than .500 mm. This, together with the difficulties involved in finding the true size distribution of quartz, outlined earlier, probably explains why the sorting of this mineral is slightly poorer than that of the heavy mineral fractions.

(c) <u>The Inclusive Graphic Standard Deviation Sorting Coefficients</u>

In order to confirm the sorting coefficients obtained by Trask's method, and to assess the environment of deposition from a different point of view, the sorting coefficients according to the inclusive graphic standard deviation method developed by Folk (1961) were calculated for zircon, chromite, and leucoxene distributions from the Main Reef Leader (East Rand). In this method, the sorting is determined by substituting the values of the 95, 84, 16, and 5 percentiles, in phi units, in the following formula :-

$$\sigma_I = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

The results so obtained are presented below.

Sample	Zircon	Chromite	Leucoxene
Geduld	.644	.482	.486
Vlakfontein	.681	.546	.498
S.A. Lands	.680	.507	.562
Daggafontein	.669	.642	.615
East Geduld	.531	.508	.492
Spaarwater	.681	.483	-
Van Dyk	.570	-	.482
Sub Nigel	.671	.575	.494
Grootvlei	.515	.497	.513
Modder East	.639	.485	-
Vogelstruisbult	.597	.471	.551
Marievale	.599	.532	.530
East Daggafontein	.582	.513	-

The sorting attributes, as calculated by the inclusive graphic standard deviation method, agree fairly well with the sorting coefficients calculated by the Trask method. As in the case of the Trask values, sorting of the zircon distributions is invariably poorer than the sorting of the accompanying chromite and leucoxene fractions. Sorting of the chromite and leucoxene distributions is generally similar, without large changes in the values.

The environmental significance of the results is of interest, and affords good confirmation of the environmental significance of the results obtained by using Trask's sorting coefficient. According to Folk (1961), most beach sands, considering a range of sands with mean sizes between 1 ∅ and 3 ∅, have sorting values of between .25 - .50 ∅, whereas most river sands have values of between .35 - 1.00 ∅. Some overlap in these values is apparent, and is to be expected. The values of sorting obtained for zircon clearly indicate deposition under fluviatile conditions, but, as has been pointed out earlier, these values are probably influenced to some extent by the shape of the zircon grains. The sorting values for the chromite and leucoxene distributions are probably more reliable as an indication of the type of depositional environment. It is clear from these values, as in the case of the Trask values, that the depositional environment could have contained both fluviatile and beach components, probably with the fluviatile component dominant.

(d) The Significance of the Results

It is apparent from the results obtained that the sorting attributes of both heavy mineral and quartz distributions within the matrix, whether calculated according to Trask's sorting coefficient or the inclusive graphic standard deviation of Folk, are useful for determining the directions of transport, and the environment of deposition of the conglomerates under investigation.

There is a definite tendency for large grains to be more poorly sorted than small grains, and this trend takes place away from assumed points of entry of reef material. It seems likely that poorer sorting is characteristic of areas close to entry points of reef material, and that deposition took place dominantly under fluviatile conditions in such areas. Indications are that the relatively well-sorted mineral distributions are characterised by smaller median grain-sizes, and that they are diagnostic of deposition under possible beach conditions. A considerable overlap, however, exists between the sorting values characteristic of fluviatile environments and those characteristic of beach environments. As most of the values obtained in the present investigation fall within this overlap, it is difficult to state emphatically what type of environment was present at the time of reef deposition. It is possible to visualize a regressing and transgressing shoreline introducing complications to the patterns. Good evidence of a fluviatile environment in the northeast central part of the East Rand is afforded by the well-developed payshoots and relatively poor sorting of the mineral constituents. As the southern and southeastern edges of the basin are approached, however, payshoots are poorly developed or non-existent, and this feature, together with the relatively good sorting of the mineral distributions, is indicative of a beach, rather than a fluviatile, environment.

Taking into consideration the three reefs studied, the conclusions can be drawn, from the sorting values obtained, that fluviatile conditions, which existed near the presumed entry points of reef material, gave rise to a shallow-water beach environment away from the entry point and further into the basin of deposition.

G. THE SKEWNESS OF THE GRAIN-SIZE DISTRIBUTIONS

The skewness of a particular grain-size distribution measures the symmetry. Perfect symmetry has a value of zero, and all other values are either positive or negative, depending on the direction in which the curve is skewed. If a particular distribution is positively skewed, coarser admixtures exceed the fine, and if negatively skewed the converse is true (Pettijohn, 1957).

The skewness values (Sk) of all the mineral components studied are given in Table IV. From the results obtained, it is seen that most of the size distributions are very symmetrical. There is no difference in the skewness values of particular mineral species, and results from all three reefs under examination are very similar. No down-current decrease in skewness (as noted by Plumley, 1948), or correlation between the median grain-size and skewness is apparent.

Little is known about the significance of skewness values obtained from heavy mineral and quartz distributions. Hough (1942), quoted by Pettijohn (1957), noted that the medium-grained beach and near-shore sands of Cape Cod Bay had a symmetrical size distribution curve, i.e. one with no skewness, and showed that beach sands (median .57 mm.) had a skewness of .02. It has also been noted that the finer the sediment, the more skewed it is. The results of skewness calculations given by Pettijohn (1957, p. 351) are in accordance with those obtained by Hough, and indicate that the size distribution curves of sand from marine environments are symmetrical and show little, if any, skewness. From the above, it is suggested that the heavy mineral and quartz particles of the matrix of the reefs under examination, have been deposited in a near-shore, shallow water, beach environment.

THE HYDRODYNAMIC CONDITIONS OF DEPOSITION

A. CUMULATIVE CURVES

The isopleth maps indicate that some size relationship must hold between the heavy mineral constituents. All the contours indicate that there is a systematic, sympathetic decrease in the median grain-sizes of heavy minerals in particular directions. It appears likely that the size relationship between the heavy minerals is due to the fact that the various fractions are in hydraulic equilibrium with each other. Most of the cumulative curves (6 representative examples of which are shown in Figures 15 and 16) of heavy mineral constituents in a particular sample are parallel to each other.

Despite the general parallel nature of the curves, a number of minor discrepancies are worthy of note. The curves for zircon often tend to transgress across the neighbouring curves, especially in the coarser and finer grades. This indicates that the zircon distributions generally have slightly poorer sorting than the other heavy mineral distributions. The reason for such a distribution, as outlined previously, is due to the fact that the mineral is prismatic in form, and thus differs from the other minerals under investigation, none of which is prismatic. Since grain-size is defined as the maximum horizontal intercept, it is obvious that there will be a larger spread in the size distribution of zircon. The cumulative curves for rounded pyrite, and arsenopyrite plus glaucodot (where sufficient grains are present for statistical analysis) are very similar to those of leucoxene, chromite, and zircon. The characteristic position of the pyrite curve is intermediate between the curves for leucoxene and zircon. Leucoxene curves indicate that the mineral from which the leucoxene was derived was the largest heavy mineral component. Small discrepancies in the curves for pyrite and leucoxene are probably due to the incorrect distinction between rounded and crystalline pyrite in the former case, and to inaccurate interpolation of size, as well as the possible effect of a varied origin, in the case of leucoxene. The cumulative curves for quartz of sand grade size are usually fairly erratic due to the difficulty of obtaining a true size distribution. The size distribution of the quartz fraction is influenced, especially in the finer grades, by splintered angular particles, the effect of which on the relative sizes of equally-settling grains is not known. The expression of size distributions as number frequencies has the disadvantage of overlooking the abundance of grains in the smaller size classes. In addition, empaction of authigenic quartz on original rounded grains, and the replacement of the edges of allogenic quartz has often concealed the true nature of the grain. The cumulative curves are, however, generally similar to the curves depicting the heavy mineral distributions.

B. HYDRAULIC RATIOS

In order to test the validity of the assumption that leucoxene and pyrite are, in fact, detrital minerals, or that they have been derived from some pre-existing detrital mineral, calculations of hydraulic equivalent ratios were made. If the median grain-size of a particular mineral is divided by the median grain-size of another mineral, of the same specific gravity, in the same sample, a ratio of one should be obtained, if the minerals under investigation are in hydraulic equilibrium. This ratio should remain relatively constant (within experimental error, and irrespective of changes in the median grain-size) in other parts of the horizon, provided the minerals being investigated are in hydraulic equilibrium. Similarly, if the ratios of the median grain-sizes of two mineral species with different specific gravities are computed, the result obtained for the same minerals from different areas of the same horizon should be constant, or nearly so, irrespective of median grain-size or sorting, if the minerals were deposited under the same hydraulic conditions. This would only hold, provided complicating factors such as particle shape, or the relative availability of the different size fractions, do not arise.

In the present investigation, chromite was chosen as a suitable mineral for obtaining these ratios. Chromite within the banket is generally regarded as being of undoubted detrital origin, and, furthermore, the grain shape of this constituent is very similar to that of leucoxene and pyrite. Zircon could probably be used as effectively to obtain the ratios, but the size distribution of the mineral, as indicated by the cumulative curves, is not quite in accordance with the distribution of other heavy mineral components, because of the elongated nature of some of the grains. Hydraulic equivalent ratios for chromite/leucoxene, chromite/pyrite, and chromite/zircon were calculated as follows :-

Sample Locality	Md Chromite / Md Leucoxene	ratio	Md Chromite / Md Pyrite	ratio	Md Chromite / Md Zircon	ratio
Geduld	.278 / .398	.697	-	-	.278 / .291	.955
Daggafontein	.262 / .396	.661	.262 / .296	.885	.262 / .281	.932
S.A. Lands	.261 / .390	.669	.261 / .305	.855	.261 / .286	.912
Vlakfontein	.235 / .380	.618	-	-	.235 / .288	.815
Grootvlei	.249 / .355	.701	.249 / .272	.915	.249 / .227	1.090
Sub Nigel	.193 / .311	.620	.193 / .261	.736	.193 / .230	.839
Modder East k4710-k4714	.224 / .299	.749	-	-	.224 / .215	1.041
Modder East k4701-k4707	.221 / .280	.788	.221 / .280	.789	.221 / .220	1.004
Marievale	.161 / .270	.596	.161 / .188	.856	.161 / .178	.904
Vogelstruis-bult	.173 / .262	.660	.173 / .199	.869	.173 / .189	.915
East Geduld	-	-	.278 / .298	.932	.278 / .263	1.050
Spaarwater	-	-	-	-	.215 / .259	.830
East Dagga-fontein	-	-	.165 / .190	.868	.165 / .160	1.030
C.M.R.	-	-	.272 / .287	.947	.272 / .318	.855
Libanon	-	-	.300 / .334	.898	.300 / .282	1.060
Venterspost	-	-	.261 / .359	.727	.261 / .296	.881
West Drie-fontein	-	-	.226 / .237	.953	.226 / .217	1.040
Doornfontein	-	-	.198 / .240	.825	.148 / .188	.787

It can be seen that the ratios remain relatively constant. The ratio between chromite and zircon was calculated as a test of the validity of this method. Theoretically, this ratio should remain constant at about one (both minerals are of almost the same specific gravity), if the minerals are in hydraulic equilibrium. Departures from the theoretical ratio are not very great and are probably within the limits of experimental error.

It should be borne in mind that the samples used in this investigation were not specially chosen according to the degree of preservation or abundance of particular heavy mineral constituents. From the results obtained, it is concluded that leucoxene and pyrite (in rounded form) are in hydraulic equilibrium with zircon and chromite, and are therefore of detrital origin.

In order to further substantiate the above conclusion, the median grain-sizes of leucoxene and chromite, of pyrite and chromite, and of zircon and chromite were plotted on two-component scatter diagrams (see Figure 17a, b, and c). A linear arrangement of points is apparent in all cases. Assuming the hydraulic ratios obtained had been exactly equal, then, if the median grain-sizes of the two components from which the ratios had been derived were plotted on a two-component diagram, a perfectly straight line or linear function would result. This would mean a 100% certainty that the minerals being investigated were in hydraulic equilibrium with each other. It is possible to calculate the following correlation coefficients (Moroney, 1962) from the data, giving a statistical appraisal of the chances of the lines (or linear patterns) obtained being straight-line functions.

leucoxene against chromite	.9769
pyrite against chromite	.8160
zircon against chromite	.7995

Statistical analysis has shown that most correlation coefficients above .65 are good indications that a straight-line function does exist.

From the figures it is seen that the correlation coefficient for leucoxene against chromite is very good, and that the correlation coefficients for pyrite against chromite, and zircon against chromite are good. It is significant that the values obtained for leucoxene/chromite and pyrite/chromite are better than the values obtained for zircon and chromite, undoubted detrital minerals. It is therefore highly probable that zircon, chromite, leucoxene, and pyrite are in hydraulic equilibrium with each other.

The sympathetic grain-size decrease of heavy mineral constituents is shown in Figure 18 which provides a visual indication of the hydraulic relationship between the median sizes of heavy mineral distributions. In Figure 18a, the median grain-sizes of zircon, chromite, leucoxene, and pyrite in the Main Reef Leader (East Rand) have been plotted against sample locality. Zircon has been taken as a standard of reference. The grain-size of this mineral constituent decreases progressively from the left to the right of the diagram, and points have been joined by a solid black line. Similar lines for the other mineral constituents, although not conforming exactly to the plot for zircon, indicate that there is a general sympathetic size decrease from the left to the right of the diagram. The plots obtained for leucoxene and chromite coincide remarkably closely, probably as a result of the similar grain shape of these minerals. The plots for zircon and pyrite are fairly similar, and differ slightly from the plots for leucoxene and chromite. In all cases, however, there is a distinct tendency of grain-size decrease to the right of the diagram. In Figure 18b, the median grain-sizes of zircon and leucoxene in the Main Reef Leader of the Central Rand have been plotted against sample locality. In this case, leucoxene has been taken as a standard of reference, and the grain-size of this mineral decreases progressively from the left to the right of the diagram. There is again a decided tendency of decrease in grain-size from the left to the right of the diagram. In Figure 18c, the median grain-sizes of zircon, chromite, and pyrite have been plotted against some of the sample localities of the Main Reef. Chromite has been taken as a standard, and the general size decrease of all constituents from the left to the right of the diagram is again apparent.

The numbered sampling localities employed in Figure 18 occur within the following mines :

FIGURE 18a

1.	Geduld Proprietary Mines Ltd.	Geduld
2.	Vlakfontein Gold Mining Co. Ltd.	Vlakfontein
3.	S.A. Lands and Exploration Co. Ltd.	S.A. Lands
4.	Daggafontein Mines Ltd.	Daggafontein
5.	East Geduld Mines Ltd.	East Geduld
6.	Spaarwater Gold Mining Co. Ltd.	Spaarwater
7.	Van Dyk Consolidated Mines Ltd.	Van Dyk
8.	The Sub-Nigel Ltd.	Sub-Nigel
9.	Grootvlei Proprietary Mines Ltd.	Grootvlei
10.	Modderfontein East Ltd. Samples k4701 - k4707	Modder East
11.	Modderfontein East Ltd. Samples k4710 - k4714	Modder East
12.	Vogelstruisbult Gold Mining Areas Ltd.	Vogelstruisbult
13.	Marievale Consolidated Mines Ltd.	Marievale
14.	East Daggafontein Mines Ltd.	East Daggafontein

FIGURE 18b

1.	Crown Mines Ltd. Sample 8	Crown Mines
2.	East Rand Proprietary Mines Ltd. Sample 2	E.R.P.M.
3.	Crown Mines Ltd. Sample 5	Crown Mines
4.	Rose Deep, Ltd.	Rose Deep
5.	Consolidated Main Reef Mines and Estates Ltd.	C.M.R.
6.	East Rand Proprietary Mines Ltd. Sample 9	E.R.P.M.
7.	Crown Mines Ltd. Sample 7	Crown Mines
8.	Crown Mines Ltd. Sample 6	Crown Mines
9.	City Deep Ltd.	City Deep

FIGURE 18c

1.	Libanon Gold Mining Co. Ltd.	Libanon
2.	Consolidated Main Reef Mines and Estates Ltd.	C.M.R.
3.	Venterspost Gold Mining Co. Ltd.	Venterspost
4.	West Driefontein Gold Mining Co. Ltd.	West Driefontein
5.	Doornfontein Gold Mining Co. Ltd.	Doornfontein

C. HYDRAULIC EQUIVALENTS

Hydraulic equivalents are useful as a means of deciphering the original nature of some of the more problematic minerals within the matrix, on the basis of specific gravity. In this investigation, hydraulic equivalents were used primarily in an attempt to decipher the original nature of the rounded grains of leucoxene and pyrite occurring within the matrix. The hydraulic equivalent is a measure of the distance between the median grain-size of the quartz distribution in a particular sample and the median grain-sizes of corresponding heavy mineral distributions. These values are read in phi units. The hydraulic equivalent of a particular mineral is therefore dependant on the specific gravity of that mineral. If, for example, a particular heavy mineral has a relatively high specific gravity, then its distributive curve will be relatively far removed from the distributive curve of quartz in the same sample, and it will have a correspondingly large hydraulic equivalent value. If, on the other hand, a particular heavy mineral has a relatively low specific gravity, then its distributive curve will be relatively close to the distributive curve for quartz in the same sample, and it will have a correspondingly small hydraulic equivalent value. From the table given by Rittenhouse (1943), the hydraulic equivalent for magnetite (S.G. 5.2) is 1.0, whereas the hydraulic equivalent for titanite (S.G. 3.5) is .5. It is thus apparent that if the hydraulic equivalents of leucoxene and pyrite distributions within the banket are calculated, bearing in mind that these minerals are in hydraulic equilibrium with known detrital minerals such as zircon and chromite, some idea of the original nature of these minerals can be obtained. In order to determine the hydraulic equivalent numbers therefore, it is necessary to know the size distribution of quartz of the sand grade fraction. From an examination of the cumulative curves representing the size distributions of quartz, it is apparent that, although roughly parallel to the curves for the heavy minerals, they are not generally suitable as a standard of comparison. Most of the curves become less steep in the coarse grain fractions, and the difficulties involved in obtaining a true picture of the quartz distributions have been discussed previously. In some cases, however, it is possible to obtain a fairly representative appraisal of the size distribution of the mineral. In such instances abundant silt and phyllosilicates within the matrix facilitate the measurement of sand size particles of quartz. The hydraulic equivalents of chromite, zircon, leucoxene, and pyrite were calculated, where such conditions prevailed. The results represent the average of 4 readings for every mineral.

Mineral	S.G.	Hydraulic Equivalent Numbers
Chromite	4.7	.94
Zircon	4.7	.93
Pyrite	4.9	.87
Leucoxene	?	.51

The result obtained for zircon (.93) is very similar to the result (.9) obtained for the same mineral by Rittenhouse (1943). The hydraulic equivalent number for chromite would be expected to be about the same as that of zircon, because the minerals have similar S.G.'s, and, as can be seen from the above table, this is the case.

The hydraulic equivalent number for pyrite (about the same specific gravity as zircon and chromite) would be expected to be slightly higher than the observed result of .87. It is obvious from the median grain-size that pyrite grains are always slightly larger than accompanying zircon and chromite grains. If pyrite were in hydraulic equilibrium with the latter minerals, as has been shown, it would be expected that the median grain-size of this mineral would be closer to the median grain-sizes of chromite and zircon in a particular sample. In order to explain this apparent anomaly as regards the size of pyrite grains, it is necessary to enquire into the genetic significance of the rounded pyrite within the banket. That the pyrite is of detrital origin, and has been deposited together with other heavy minerals, seems to be beyond doubt. It has been contended that the compact rounded pyrite grains within the matrix represent the pseudomorphous replacement product of original rounded hematite or magnetite grains, or components generally referred to as "black sands". It is clear from mineralogical evidence that some of the pyrite and leucoxene grains have been derived from minerals such as titan magnetite, and, in the case of leucoxene, ilmenite. Such grains, however, only account for a small proportion of the total rounded pyrite grains in the reefs under investigation. Suppose that the bulk of the rounded pyrite grains had been derived from hematite (S.G. 5.2) or magnetite (S.G. 5.1 - 5.2), then it would be expected that the hydraulic equivalent number would be about 1.0 (Rittenhouse, 1943), which is not the case. If it is assumed that the concept of hydraulic equivalent sizes is acceptable, as appears to be the case, then an explanation of the anomalous size distributions of pyrite has to be sought. It is apparent from the above, therefore, that the hydraulic equivalent number of .87 obtained for pyrite, which has a lower specific gravity (4.8 - 5.0) than hematite or magnetite, appears to be more compatible with the idea that the original mineral was, in fact, pyrite and not magnetite or hematite, or any other "black sand" constituent. This being the case, the observed size of the pyrite distributions is still too high. A possible explanation is sampling error, but the constant larger median grain-sizes of the pyrite distributions seem to preclude this possibility. Rittenhouse (1943) noticed fairly large discrepancies in the hydraulic equivalent numbers calculated by him, and contended that these differences were due to some unknown factor. Zircon grains were described as occurring in a sediment, which were actually finer-grained than the accompanying magnetite fraction, despite the fact that magnetite has a higher specific gravity. Van Andel (1959) found that grains of pyroxene occurring in the Rhone River were restricted to the coarse fraction of the detritus, epidote to the fine fraction, and hornblende to the intermediate fraction, in spite of the fact that these three mineral groups have approximately the same density. According to him, these discrepancies are due to the relative availability of different size fractions of a particular mineral in the source area.

It is thought likely that the observed sizes of rounded pyrite grains in the reefs under investigation are due to the availability of this mineral, relative to other heavy mineral constituents, in the source area. The great abundance of rounded pyrite grains (as well as other forms of pyrite) within the matrix indicates that this sulphide must have been extremely abundant in the source area, relative to chromite and zircon. Whereas pyrite was available in particles up to one cm. or more in size (as evidenced by large grains of buckshot pyrite not of the replacement variety), chromite and zircon particles, by nature of their origin, would be expected to occur as considerably smaller particles. Van der Vyver (1956) and Winter (1957) have noted that the coarse, or buckshot, type of pyrite is most abundant in a robustly developed reef fairly close to an original shoreline or entry point of reef material. It is obvious that zircon or chromite grains could never attain this size under normal conditions. It is concluded therefore that the abundance of pyrite in the source area, together with the original larger possible grain-size of the mineral (as compared to zircon and chromite) has influenced the size distribution, giving the larger average grain-sizes observed.

Leucoxene is the largest heavy mineral, of original detrital origin, under investigation, and the hydraulic equivalent number of this constituent is .51. The relatively large size of the leucoxene grains is readily apparent from the cumulative curves (see Figures 15 and 16) which occupy a position roughly intermediate between the curves depicting the chromite and zircon distributions and the curves representing the quartz distributions. It is commonly believed that the leucoxene within the banket has been derived from some pre-existing titanium-bearing mineral, such as ilmenite or sphene. Supposing that the original mineral from which the leucoxene was derived had been ilmenite (S.G. 4.7), the hydraulic equivalent of which is 1.0 (Rittenhouse, 1943), then one would expect the median sizes of the leucoxene distributions to be similar to the median sizes of the accompanying chromite and zircon distributions, the latter two minerals having approximately the same S.G. as ilmenite. It is obvious, in all the samples studied, that this is not the case, and the median sizes of the leucoxene distributions are always significantly larger than the median sizes of accompanying zircon and chromite distributions. It seems likely, therefore, that some titanium-bearing mineral, other than ilmenite, and with a lower specific gravity than the latter, must have given rise to the leucoxene. It has been suggested that some of the leucoxene has been derived from sphene (S.G. 3.5) and radioactive sphene (Liebenberg, 1955). In support of the contention that a fairly large amount of the leucoxene has been derived from sphene is the fact that the hydraulic equivalent number obtained for leucoxene in the present investigation (.51) is very close to the value of .5 obtained by Rittenhouse (1943) for sphene.

It is tentatively concluded that the original, and most important mineral, which gave rise to the leucoxene was sphene, radioactive sphene, or a titanium-bearing mineral with a similar specific gravity, and that, only a limited percentage was derived from ilmenite. The reason for the above reservations is the fact that the measurement of an altered constituent is not easy. Production of leucoxene from an original titanium-bearing mineral usually results in a mobilized product which tends to increase the size of grains. In addition, if the original grains had been ilmenite, the abundance and size of the mineral in the source area could, as in the case of the pyrite, affect the grain size.

THE NATURE AND ORIGIN OF THE REEFS IN THE LIGHT OF QUANTITATIVE MINERALOGY

A. RELATIONSHIP BETWEEN GRAIN-SIZE AND GOLD VALUES

One of the main conclusions to be drawn from the investigation is that there is a correlation between the size of heavy mineral components within the matrix and the tenor of gold mineralization. Whereas portions of reef characterized by high gold values contain large heavy mineral components, areas of reef containing low or erratic gold values generally contain smaller heavy mineral components.

In the East Rand the economically most important sector corresponds closely with the isopleths for the larger heavy mineral constituents. The amount of gold in the Main-Bird Series is much greater in this section than elsewhere. The following mine properties, which have yielded large amounts of gold, fall within this area :- New Kleinfontein, Van Ryn Deep, New Modder, Modder Deep, Modderfontein, Government Gold Mining Areas, Geduld, New State Areas, Daggafontein, Springs, Brakpan, and parts of S.A. Lands and Vlakfontein. On the other hand, small heavy mineral components generally correspond with areas of overall low gold values. Mine properties which contain small heavy mineral components, such as Holfontein, Welgedacht, the eastern portions of Grootvlei, East Daggafontein and Marievale, Nigel, Wit Nigel, parts of Spaarwater and Sub Nigel, West Spaarwater, West Vlakfontein, Withok, and portions of Van Dyk, generally contain relatively low gold values and generally poorly-developed reef which may, in places, grade into a grit band or completely disappear.

In the Main Reef Leader and Main Reef of the Central Rand the same relationship holds. The large sizes of heavy mineral components in the northern portion of Crown Mines and Village Main Reef Mine are indicative of exceptionally high gold values. In the early days of mining, part of this area was known as the "Golden Mile", and included such mines as the Langlaagte Mine, the Village Main Reef Mine, and the Bonanza Mine, situated on the common mine boundary between Crown Mines and the Village Main Reef Mine. Before mining operations ceased, these mines produced exceptionally high values of gold per ton of ore mined. Between August, 1896, and March, 1908, for example, the Bonanza Mine gave an average recovery grade of 17.3 dwts. of gold per ton. The Robinson and Ferreira mines, which adjoined the Bonanza, yielded averages of 9.9 and 9.5 dwts. per ton respectively (Pretorius, 1963). It is significant, too, that the Village Deep (average recovery grade of 6.4 dwts. per ton) and the Crown Mines (5.2 dwts. per ton) have been amongst the richer deep-level mines of the Central Rand (Pretorius, 1963). The relatively large sizes of the heavy mineral components in the E.R.P.M. area are accompanied by relatively high gold values. Conversely, parts of the Main Reef Leader and Main Reef in the Central Rand containing smaller heavy mineral components are characterized by generally lower gold values. The tenor of gold in mines such as Simmer and Jack, City Deep, and parts of Robinson Deep, in the east, and the Durban Deep, Rand Leases, and parts of the C.M.R., in the west, generally contain lower gold values than the Crown Mines and E.R.P.M. areas.

A similar relationship between large heavy mineral constituents and high gold values appears to hold for the Main Reef outside the Central Rand area, i.e. in the West Rand and West Wits Line. Insufficient samples were studied, however, to give more positive indications of this relationship.

The relationship between high gold values and large heavy mineral components is such that it is possible to suggest the sizes of heavy mineral components (within a relatively narrow range) which should theoretically delimit the zone of payability in a particular conglomerate reef. It should be noted here that the size of quartz particles within the matrix generally bears a relationship to the size of the heavy mineral components. Due to the difficulty of measuring these grains, however, and to the relatively large variation in size of this mineral, quartz is considered to be an unsuitable mineral for delimiting zones of payability in a particular reef. The results presented in the following table give a rough estimate of the lower size limit of various heavy mineral components which could theoretically delimit the zone of payability. The figures given are based on the isopleth maps. It should be noted that the sizes are defined as the maximum horizontal intercept of a particular mineral species, as measured in section, and are therefore smaller than the actual size. Furthermore, they apply only to the Main Reef, Main Reef Leader, and Main Reef Leader (East Rand), and it is not known whether they are applicable to other gold-bearing reefs within the Witwatersrand System.

Taking a rough average of mineral size for each species, it seems likely that, if the zircons in a particular reef have a median grain-size of about .180 mm. or less, the chances are that the reef will have a low order of payability. For chromite, this limiting size is about .165 mm., for leucoxene about .250 mm., and for pyrite .200 mm.

It should be noted that the results given in the following table apply only on a regional scale, and there are a number of factors which have to be borne in mind in determining whether or not a reef will be payable. It seems apparent that in most instances high gold values are associated with original larger detrital grains of gold which are, in turn, associated with larger heavy minerals and larger pebbles. For example, in the samples from Crown Mines referred to previously and for which camera lucida drawings have been made to illustrate the size distribution of zircon grains, the larger zircon grains, taken from the sample which is nearer the presumed entry point of reef material are associated with higher gold values. In addition, the size of the pebbles in this sample is distinctly larger than the pebbles in the sample taken at depth, which has low gold values. Assume that a mixture of large clastic constituents (i.e. large pebbles plus relatively large grains of gold and heavy mineral constituents) were brought into a basin of deposition together with smaller constituents (i.e. smaller pebbles plus relatively small grains of gold and heavy mineral constituents). As this material fanned out in the depositional basin, the larger constituents in hydraulic equilibrium with each other, i.e. the pebbles plus grains of gold and heavy mineral constituents, would tend to be deposited near the entry point of reef material because of the competency of the transporting current diminishing progressively further away from this point. As the rest of the material was swept further into the basin, so smaller and smaller constituents would be deposited by the process of selective sorting. A stage would come when there would be an accumulation of small well-sorted pebbles plus grains of gold and other heavy mineral constituents in relative abundance.

Mineral	Reef	Range of grain-size delimiting pay areas	Average grain-size delimiting pay areas
Zircon	M.R.L. (E.R.)	.200 - .160 mm.	.180 mm.
	M.R.L. (C.R.)	.200	.200
	M.R. (C.R.)	.180	.180
	(W.R.)	.200 - .180	.190
	(W.W.L.)	.200 - .190	.195
Chromite	M.R.L. (E.R.)	.180 - .160	.170
	M.R.	.170 - .150	.160
Leucoxene	M.R.L. (E.R.)	.260 - .240	.250
	M.R.L. (C.R.)	.270 - .240	.255
Pyrite	M.R.L. (E.R.)	.200 - .180	.190
	M.R. a (W.W.L.)	.210 - .190	.200
	b	.230	.210
	c	.220	.200

This was found to be the case during the present investigation, where the reef relatively close to original entry points was found to be composed of large pebbles with large, but scattered, heavy mineral constituents in no great abundance. The size of the gold particles could not be measured because of remobilization and recrystallation after deposition, but the high tenor of gold in such areas could possibly be taken as an indication that the original detrital grains of gold were relatively large. On the other hand, reefs at the outer edges of the depositional basins were almost invariably found to be composed of generally smaller pebbles set in a matrix which contains a relatively large number of small heavy mineral constituents, with moderate to poor gold values. It would be expected that a high concentration of heavy minerals would be a manifestation of a high concentration of gold grains, and, therefore, of rich reef. This might be the case in some areas where the original detrital grains of gold were relatively small. In such cases, the process of selective sorting would assure relatively good, but probably patchy, gold values in the marginal areas of a depositional basin. The size of the original gold particles is, therefore, thought to be of prime importance in determining which part of a reef will be the most suitable as far as high gold values are concerned, and in determining the character of reef in such cases. The above probably applies only on a regional scale and very much more detailed work would be needed to demonstrate the effect of sorting or concentrating processes superimposed on this primary pattern. For example, elevated areas in the depositional basin and the possibility of truncation of earlier gold-bearing horizons could give rise to local or fairly extensive areas of higher gold values.

From the quantitative evidence available, it is concluded that gold is a detrital mineral, and that it is in hydraulic equilibrium with other heavy mineral constituents. The hydraulic conditions under which the mineral was deposited and the proximity to entry points determine whether a reef is payable in particular areas.

B. DISTINCTIVE AREAS OF DEPOSITION

From the results obtained and from recent work on the East, Central, and West Rand (D.A. Pretorius, verbal communication), it is apparent that the reefs under examination are not continuous sheets of conglomerate, as has previously been supposed. It is possible, on the contrary, to be able to divide each reef into a number of units or cells, each cell representing an ancient depositional depression fed by its own river system which as a rule debouched into the depression at a well-defined entry point. The depth of these depressions was, however, not very great, so that material from one area often intermingled with material from an adjacent unit. Thus, in many cases, the only indication of the inter-depression zones is a slight thinning of a particular horizon, with decreasing robustness of the reef and a corresponding drop in the tenor of gold values. The intermixing of reef material from adjacent cells gave the reef a relatively uniform nature and mineral composition over large areas. The most significant feature of these entry points and depressions of deposition of reef material is that the reef in the immediate entry point area is often associated with high gold values which steadily decrease in a downstream direction into the particular depression. The present mineralogical study has made it possible to identify at least four, and possibly five, depositional units in the reefs investigated. It is probable that these depositories and their corresponding entry points retained their relative geographic positions during the period of sedimentation which gave rise to the Main Reef and Main Reef Leader. The individual depressions, which acted as traps for reef material composing the three reefs under investigation, as deduced mainly from the evidence of heavy mineral isopleths, but supported by other mineralogical evidence, are as follows (see Figure 20) :-

(i) The Main Reef Leader (East Rand) forms a distinct depositional unit, as is indicated by the closure of the isopleth pattern. It is apparent that the material composing the reef has been derived from a point of entry to the northwest. The ratio of zircon to chromite indicates that the reef has been derived from slightly different source rocks to those composing the Main Reef Leader of the Central Rand. The relative abundance of rounded grains of arsenopyrite, glaucodot, and cobaltite, as well as the abundance of pyrrhotite, are features which are all possibly indicative of different source rocks. The complete lack of chloritoid in the reef is also of significance in this connection, and indicates that the composition of the original interstitial mud must have been different to that of the Main Reef and Main Reef Leader, both of which contain chloritoid. The reefs of the Main-Bird Series of the Central Rand are separated from similar reefs of the East Rand by a break in gold values, commonly known as the "Boksburg Gap". Although the reef is present, it is poorly developed, and the term "gap" merely refers to the poor gold values in this area. This break forms the interdepressional zone between the Main Reef Leader (East Rand) and the Main Reef, Main Reef Leader, and South Reef of the Central Rand.

(ii) A probable point of entry of reef material for both the Main Reef and Main Reef Leader of the Central Rand exists in the area to the north of the Crown Mines property. The isopleth patterns suggest, in addition, a possible point of entry in the Rose Deep - E.R.P.M. area. The similarity of the mineralogy of the individual reef horizons along strike (i.e. the ratio of the heavy minerals, the phyllosilicate content, and the ore mineralogy) suggests that the material composing the individual reefs has been derived from one entry point which retained a similar position at the time of deposition of both the Main Reef and Main Reef Leader in this area. The fact that the isopleths do not form a closure delineating individual depressions, and that the trend of some of the payshoots is rather east-west than north-south, leads to the conclusion that the transport direction was probably about W.N.W. to E.S.E. The inflection in the isopleth patterns in the Crown Mines area has probably been caused by a phase of folding, with fold axes trending roughly north-south, which occurred some time after deposition.

(iii) An entry point of Main Reef material northwest of Krugersdorp is indicated from the heavy mineral isopleths and from other mineralogical observations. Although the relative percentages of the heavy mineral components in this part of the Main Reef are similar to the percentages in the Main Reef of the Central Rand, the relative percentages of the phyllosilicates are of significance. The dominant phyllosilicates in the matrix of samples available from West Rand Consolidated, Luipaardsvlei, and Durban Roodepoort Deep is chloritoid. The gradual decrease in the chloritoid content of the matrix of the Main Reef from this area in a southerly direction (i.e. through Venterspost and Libanon to West Driefontein and Doornfontein), and in an easterly direction (i.e. through the C.M.R., City Deep, Rose Deep and E.R.P.M. mines) is distinctive. It appears as though there has been a gradual change in the composition of the interstitial matrix mud of the Main Reef from the Krugersdorp area in southerly and easterly directions. This material has probably mingled with reef material from the Venterspost - Libanon area,* and to a certain extent with the material composing the reef in the Central Rand area.

(iv) An entry point of reef material to the northwest of the Venterspost and Libanon mines is indicated by the heavy mineral sizes, as well as the ratio of zircon to chromite, which is smaller than the ratio of these minerals in the Central Rand area, and about the same as the ratio in the Main Reef Leader (East Rand).

(v) Heavy mineral sizes indicate a possible additional point of entry of reef material in the Doornfontein - West Driefontein mining area. It is probable, however, that this part of the reef is closely connected to the entry point just described. This is supported by the fact that the ratio of zircon to chromite is about the same as the ratio in the Venterspost-Libanon area, but different to the ratio elsewhere in the Main Reef.

The major anticlinal and synclinal axes in the area under investigation have been plotted on a map (see Figure 20). This area forms part of the northern limb of the main synclinorium of the Witwatersrand Basin, which strikes from southwest of Klerksdorp in an E.N.E. direction, between Potchefstroom and the Vredefort Dome, to the centre of the East Rand (Pretorius, 1963). It appears likely that reef formation was closely connected with crustal adjustments which were probably operative before, during, and after Witwatersrand times. The East Rand affords a good example of a structurally formed feature which has been responsible for the localization and deposition of reef material. The depression is roughly egg-shaped, with dips south and southeast from the northern flank, W.S.W. from the eastern flank, and N.N.W. from the southern flank. Not much is known of the western flank, but the depression appears to deepen in this area, and dips are towards the west. According to Cluver (1957), the deepest portion of the depression is in the vicinity of the West Springs, Vlakfontein, and Withok joint boundary where it is 8,000 feet below surface. This author has recognized four major folds within the depression, with axes trending roughly N.W. - S.E. (see Figure 20). It is apparent that the isopleths depicting the distribution of the largest heavy mineral components within the Main Reef Leader (East Rand) coincide closely with two major synclinal axes. This area of the depression (i.e. the N.W. central portion) contains, in addition, the greatest quantity of gold. It would, therefore, seem probable that the greatest accumulation of gold within a particular reef is intimately associated with synclinal troughs near to the points of entry of reef material into a depositional unit.

The East Rand is separated from the Central Rand area by a major N.N.W.-trending anticlinal fold axis which coincides closely with the "Boksburg Gap". This "gap" forms the inter-depressional zone between the East Rand and the Central Rand. A major break in the Main-Bird Series occurs between the Durban Roodepoort Deep Mine and the mines of the Krugersdorp area. This break is commonly referred to as the "Witpoortje Gap", where extensive horst faulting took place (the horst block being defined by the Witpoortje Fault to the northwest and the Roodepoort Fault to the southeast), and the entire Upper Division of the Witwatersrand succession has been removed. The Main Reef Leader is not developed west of the "Witpoortje Gap", but the Main Reef and other horizons of the Upper Division occupy a well-defined structural basin referred to as the West Rand Syncline. It seems likely, from evidence cited previously, that a major entry point of reef material existed to the northwest of this area, in the vicinity of Krugersdorp.

C. CORRELATION OF REEF HORIZONS

On the assumption that the reef material composing the Main Reef Leader (East Rand) has been derived from a single, confined point of entry, it seems highly unlikely that this reef can be correlated, on mineralogical evidence alone, with any of the major reef horizons (i.e. the Main Reef, Main Reef Leader, and South Reef) of the Main-Bird Series of the Central Rand. It is, however, probable that one of the three reefs occurring in the Central Rand was deposited contemporaneously with the Main Reef Leader (East Rand), and that a certain amount of reef material from both areas was mixed, possibly giving the reefs similar characteristics near the inter-depressional zone. Heavy mineral isopleth patterns indicate that there is no apparent continuation of the contours of either the Main Reef or Main Reef Leader into those of the Main Reef Leader (East Rand). If the reefs mentioned above were contemporaneous, one might have expected the reef mineralogy to be similar in the vicinity of the "Boksburg Gap". In addition, the ratios of the various heavy minerals would have been expected to be similar. This, however, is not the case, and it is concluded that neither the Main Reef or Main Reef Leader can be correlated with the Main Reef Leader (East Rand).

Although no detailed mineralogical study was carried out on the South Reef, it seems likely from the phyllosilicate mineralogy alone, that the reef has more affinities with the Main Reef Leader (East Rand) than either the Main Reef or Main Reef Leader of the Central Rand. Jones (1936) contended that, in the Central Rand area, the underlying Main Reef and Main Reef Leader have been successively transgressed by the overlying South Reef, and that the South Reef is in fact contemporaneous, and warranted correlation, with the Main Reef Leader (East Rand).

In the case of the Main Reef, the auriferous conglomerate is continuous over fairly large areas, and no special problems concerning reef correlation arise. Reef material has, however, been derived from a number of entry points, with inter-depressional anticlinal prominences causing breaks in the tenor of gold, but not necessarily in the continuity of the reef. These low anticlinal divides enabled mixing of material from different source areas to take place, giving the reef a more or less homogeneous character.

E. DEPOSITIONAL ENVIRONMENT OF THE MAIN REEF AND MAIN REEF LEADER

The type of environment under which the auriferous conglomerates of the Witwatersrand System were deposited has remained an unsolved problem. One of the main tasks involved is to explain the apparent large areal extent of the relatively thin and persistent conglomerate sheets. Difficulties arise due to the fact that the number of environments under which a conglomerate can be deposited are large, and each may pass laterally in space and time into others. For example, Twenhofel (1947) states that : "As a consequence of the deposition of coarse clastics under many environmental conditions, a conglomerate in itself has no environmental significance beyond the fact that the competency of a transporting agent was adequate to place its constituents where they are found and that a source was not too far distant whence the particles were derived". It is probably only in the case of the present-day gravels that certainty can be attached to the class to which a gravel deposit should be assigned, and a comparison of the conglomerates studied during the present investigation with present-day conglomerates is difficult. Conditions at the time of the Witwatersrand sedimentation could have been, and were probably, different to present-day conditions of sedimentation. A land surface with no vegetation, yet with high rainfall (Hargraves, 1961) and probably a cold climate must be visualized. Despite the above-mentioned limitations, it is possible, by taking a number of unrelated factors into account, to give some indication of the environment of reef deposition. According to the concept of uniformitarianism, it would be expected that the deposition of conglomerates in past geologic eras, despite different climatic conditions, was governed by the same sedimentation principles in operation today.

According to Weller (1960), the environments of deposition of gravels (conglomerates) are more clearly indicated by the form of the conglomeratic bodies and by the character of the fine-grained matrix. With these two features in mind, a fluviatile, as well as a beach, environment of reef deposition has been recognized. The following features indicate a fluviatile environment of deposition :

(i) the general, systematic decrease of the grain-size of heavy mineral constituents in a fan-shaped pattern from specific areas;

(ii) a corresponding systematic decrease in sorting values (which indicate, according to both the Trask and the Folk methods, a fluviatile environment) from the same areas, in a fan-shaped pattern;

(iii) the oligomictic character of the samples studied;

(iv) the general sub-mature nature of the matrix, which usually contains relatively large amounts of clay constituents; and

(v) the generally braided and fan-shaped payshoot patterns, especially well-developed in the Main Reef Leader (East Rand), but present in other areas, indicating fairly strong prevailing currents.

Evidence of a mixed fluviatile and beach environment is afforded by :

(i) sorting values obtained for the size distribution of the smaller heavy mineral constituents, which indicate an environment transitional between fluviatile and beach;

(ii) the symmetrical nature of the frequency distributions of heavy mineral constituents and quartz, as measured by the skewness;

(iii) comparison of eight histograms, representing the size distribution of quartz grains within the matrix, with histograms given by Weller (1960) which indicate an environment transitional between fluviatile and beach (see Figure 19); and

(iv) the sand to silt to clay ratio of the matrix of the reefs under discussion, which indicates, according to Weller (1960), deposition under shallow-water, neritic conditions.

Assessing and collating the above data, the conclusion has been reached that the main phase of deposition of the reefs under investigation took place in a fluviatile environment, probably under deltaic conditions. Reworking of the deposits so formed took place, to a variable extent, under shallow-water marine (probably beach) conditions. Areas of the delta furthest from the entry point were probably subjected to a greater degree of marine reworking, where waves and currents aided in deposition. High gold values are characteristic of areas of deposition near the apices of the deltas. An elevated land area must have existed adjacent to the depositional basins into which the conglomerates were carried, as gravels generally only accumulate in deltas fed by fast-flowing rivers.

* *

LIST OF REFERENCES CITED

Bridges, R.J. 1942 The Economic Geologist and His Work in South Africa (Anniversary Address by the President) Proc. Geol. Soc. S. Afr., 45, xxxii-xiv.

Chayes, F. 1949 A Simple Point Counter for Thin-Section Analysis. Amer. Min., 34.

Cluver, A.F. 1957 On the Tectonic History and Some Related Sedimentational Aspects of the Witwatersrand and Ventersdorp Systems in the Far East Rand, During Upper Witwatersrand Pre-Transvaal System Time. Ann. Univ. Stellenbosch, 33, Sect. A, 71-124.

Dryden, A.L. 1931 Accuracy in Percentage Representation of Heavy Mineral Frequencies. Proc. Nat. Acad. Sci., Wash., 17, 233-238.

du Toit, A.L. 1957 Geology of South Africa (3rd Ed.). Oliver and Boyd, Edinburgh, 611 pp.

Folk, R.L. 1954 The Distinction between Grain Size and Mineral Composition in Sedimentary Rock Nomenclature. J. Geol., 62, 344-359

Folk, R.L. 1961 Petrology of Sedimentary Rocks. Hemphill's, Austin, Texas.

Friedman, G.M. 1962 On Sorting, Sorting Coefficients and the Lognormality of the Grain-Size Distribution of Sandstones. J. Geol. 70, No. 6, 737-753.

Fuller, A.O. 1958 A Contribution to the Petrology of the Witwatersrand System. Trans. Geol. Soc. S. Afr., 61, 19-50.

Greenman, N.N. 1951 The Mechanical Analysis of Sediments from Thin-Section Data.
J. Geol., 59, 447-462.

Hargraves, R.B. 1961 Cross-bedding and Ripple-marks in Main Bird Quartzites in the East Rand Area : A Reconnaissance Study.
Inform. Circ. No. 5., Econ. Geol. Res. Unit, Univ. Witwatersrand, Johannesburg.

Hough, J.L. 1942 Sediments of Cape Cod Bay, Massachusetts.
J. Sed. Petrol., 12, 10-30.

Inman, D.L. 1952 Measures for Describing the Size Distribution of Sediments.
J. Sed. Petrol., 22, 125-145.

Jones, G.C. 1936 Correlation and Other Aspects of the Exploited Auriferous Horizons on the Witwatersrand Mining Field.
Trans. Geol. Soc. S. Afr., 39.

Koen, G.M. 1961 The Genetic Significance of the Size Distribution of Uraninite in Witwatersrand Bankets.
Trans. Geol. Soc. S. Afr., 64, 23-46.

Krumbein, W.C. 1934 Size Frequency Distributions of Sediments and the Normal Phi-Curve.
J. Sed. Petrol., 4, 65-77.

Krumbein, W.C. 1941 Measurements and Geological Significance of Shape and Roundness of Sedimentary Particles.
J. Sed. Petrol., 11.

Krumbein, W.C. 1953 Thin-section Mechanical Analysis of Indurated Sediments.
J. Geol., 43, 482-496.

Krumbein, W.C., and Pettijohn, F.J. 1938 Manual of Sedimentary Petrography.
D. Appleton-Century Co., New York, 549 pp.

Liebenberg, W.R. 1955 The Occurrence and Origin of Gold and Radioactive Minerals in the Witwatersrand System, the Dominion Reef, the Ventersdorp Contact Reef and the Black Reef.
Trans. Geol. Soc. S. Afr., 58, 101-223.

Marshall, P.E. 1927 The Wearing of Beach Gravels.
Trans. Proc. N.Z. Inst., 58, 507-532.

Mellor, E.T. 1915 The Upper Witwatersrand System.
Trans. Geol. Soc. S. Afr., 18, 11-57.

Moroney, M.J. 1962 Facts From Figures.
Penguin Books Ltd., Harmondsworth, Middlesex, 472 pp.

Packham, G.H. 1955 Volume, Weight and Number-frequency Analysis of Sediments.
J. Geol., 63, 50-58.

Pettijohn, F.J. 1957 Sedimentary Rocks (2nd Ed.).
Harper and Bros., New York, 718 pp.

Pirow, H. 1920 Distribution of Pebbles in the Rand Banket and Other Features of the Rock.
Trans. Geol. Soc. S. Afr., 23, 64-97.

Plumley, W.J. 1948 Black Hills Terrace Gravels : a Study in Sediment Transport.
J. Geol., 55, 526-577.

Pretorius, D.A. 1963 The Geology of the Central Rand Goldfield.
Inform. Circ. No. 13, Econ. Geol. Res. Unit, Univ. Witwatersrand, Johannesburg.

Reinecke, L. 1927 The Location of Payable Ore-Bodies in the Gold-Bearing Reefs of the Witwatersrand.
Trans. Geol. Soc. S. Afr., 30, 89-120.

Rittenhouse, G. 1943 Transportation and Deposition of Heavy Minerals.
Bull. Geol. Soc. Amer., 54, 1725-1780.

Rosenfeld, M.A., Jacobson, L., and Ferm, J.C. 1953 A Comparison of Sieve and Thin-Section Techniques for Size Analysis.
J. Geol., 61, 114-133.

Rubey, W.W. 1933 Settling Velocities of Gravel, Sand and Silt Particles.
Amer. J. Sci., 25, 325-352.

Russel, R.D., and Taylor, R.E. 1937 Roundness and Shape of Mississippi River Sands.
J. Geol., 45, 225-267.

Sharp, W.E., and Pow-Foong Fan 1963 A Sorting Index.
J. Geol., 71, No. 1, 76-83.

Smithson, F. 1939 Statistical Methods in Sedimentary Petrology.
Geol. Mag., 76, Pt. I, 297-309; Pt. II, 348-360; Pt. III, 417-427.

Steyn, L.S. 1963 The Sedimentation and Gold Distribution Pattern of the Livingstone Reefs on the West Rand.
Unpub. M.Sc. Thesis, Univ. Witwatersrand, Johannesburg.

Strydom, P.M. 1952 The Arenaceous and Rudaceous Beds in the Jeppestown Series on Brakpan Mines, Ltd., and S.A. Land and Exploration Co. Ltd. Unpub. M.Sc. Thesis, Univ. Witwatersrand, Johannesburg.

Trask, P.D. 1932 Origin and Environment of Source Sediments of Petroleum. Gulf Pub. Co., Houston.

Twenhofel, W.H. 1947 The Environmental Significance of Conglomerates. J. Sed. Petrol., 17, No. 3.

Udden, J.A. 1898 Mechanical Composition of Wind Deposits. Augustana Library Publications, No. 1.

Van Andel, I.J.H. 1959 Reflections on the Interpretation of Heavy Mineral Analysis. J. Sed. Petrol., 29, 153-163.

Van der Vyver, G.P. 1956 The Rainbow Reefs of the Van Der Heeversrust Area, Northwest of Odendaalsrus. Unpub. M.Sc. Thesis, Univ. Pretoria, Pretoria.

Weller, J.M. 1960 Stratigraphic Principles and Practice. Harper and Bros., New York, 725 pp.

Whiteside, H.C.M. 1944 Heavy Mineral Analysis of Two Reefs from the Far East Rand. Unpub. M.Sc. Thesis, Univ. Witwatersrand, Johannesburg.

Winter, H. de la R. 1957 The Upper Division of the Witwatersrand System in the Virginia Merriespruit Mining Area. Unpub. M.Sc. Thesis, Univ. Pretoria, Pretoria.

* *

KEY TO FIGURES

Figure 1 : Locality map showing mine boundaries and sampling localities.

Figure 2A : Ternary diagrams showing the relative percentages of phyllosilicates in the Main Reef Leader (East Rand), Main Reef Leader (Central Rand), Main Reef, and South Reef.

Figure 3A : Histograms showing the variations in the relative percentages of the phyllosilicates in the matrix of the Main Reef.

Figure 18 : Variations in the median grain-sizes of heavy mineral components from the reefs, from the Main Reef Leader (East Rand), the Main Reef Leader (Central Rand), and the Main Reef.

Figure 19 : Histograms representing the size distribution of sand within the matrix of 8 different samples of reef, and of sand in known present-day deposits, for comparison.

Figure 20 : Map of the area under investigation showing the main structural features, probable points of entry, and direction of transport of reef material.

* *

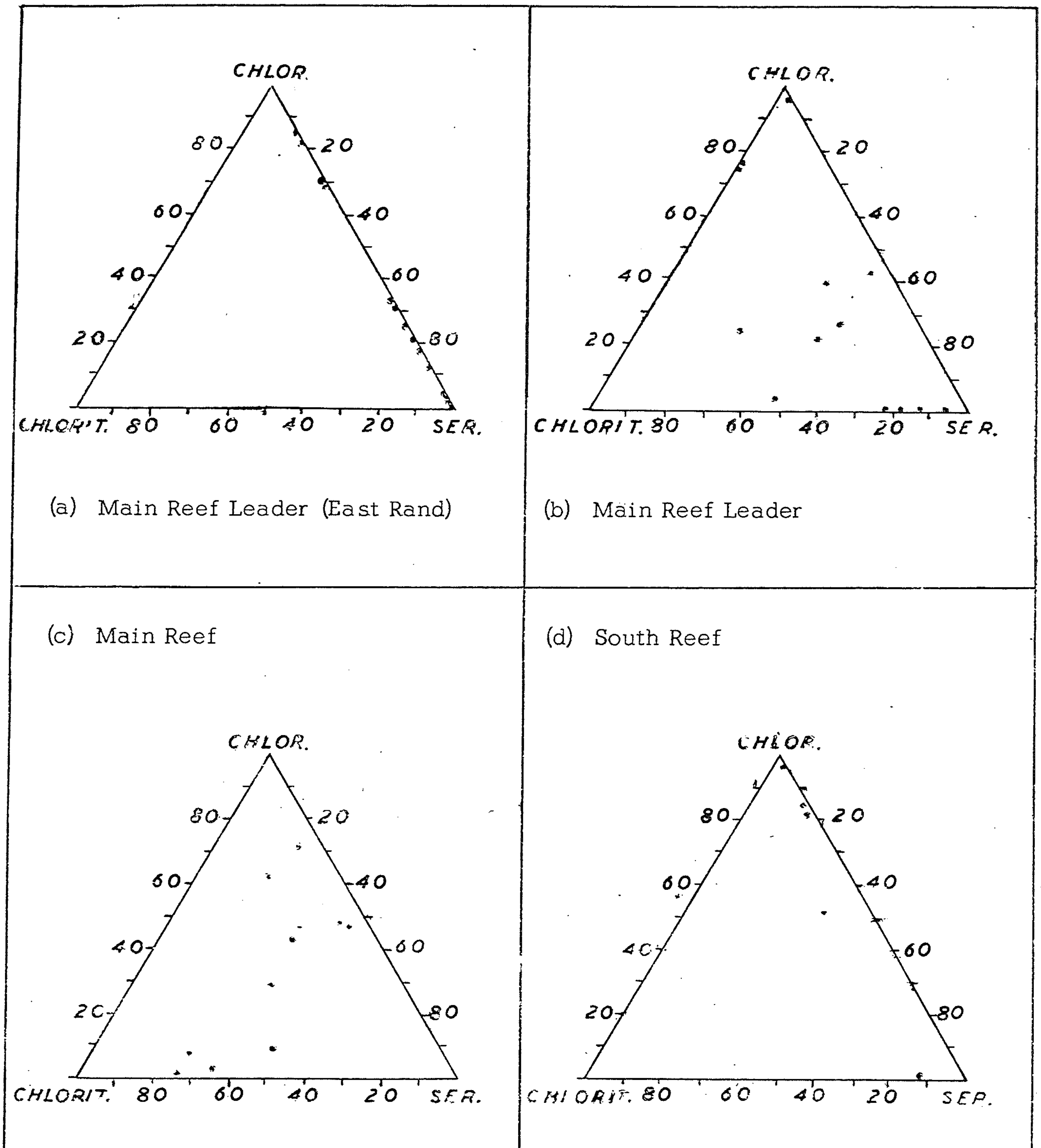


FIG. 2A : Ternary Diagrams showing the Relative Percentages of Phyllosilicates

chlor = chlorite
chlorit = chloritoid
ser = sericite

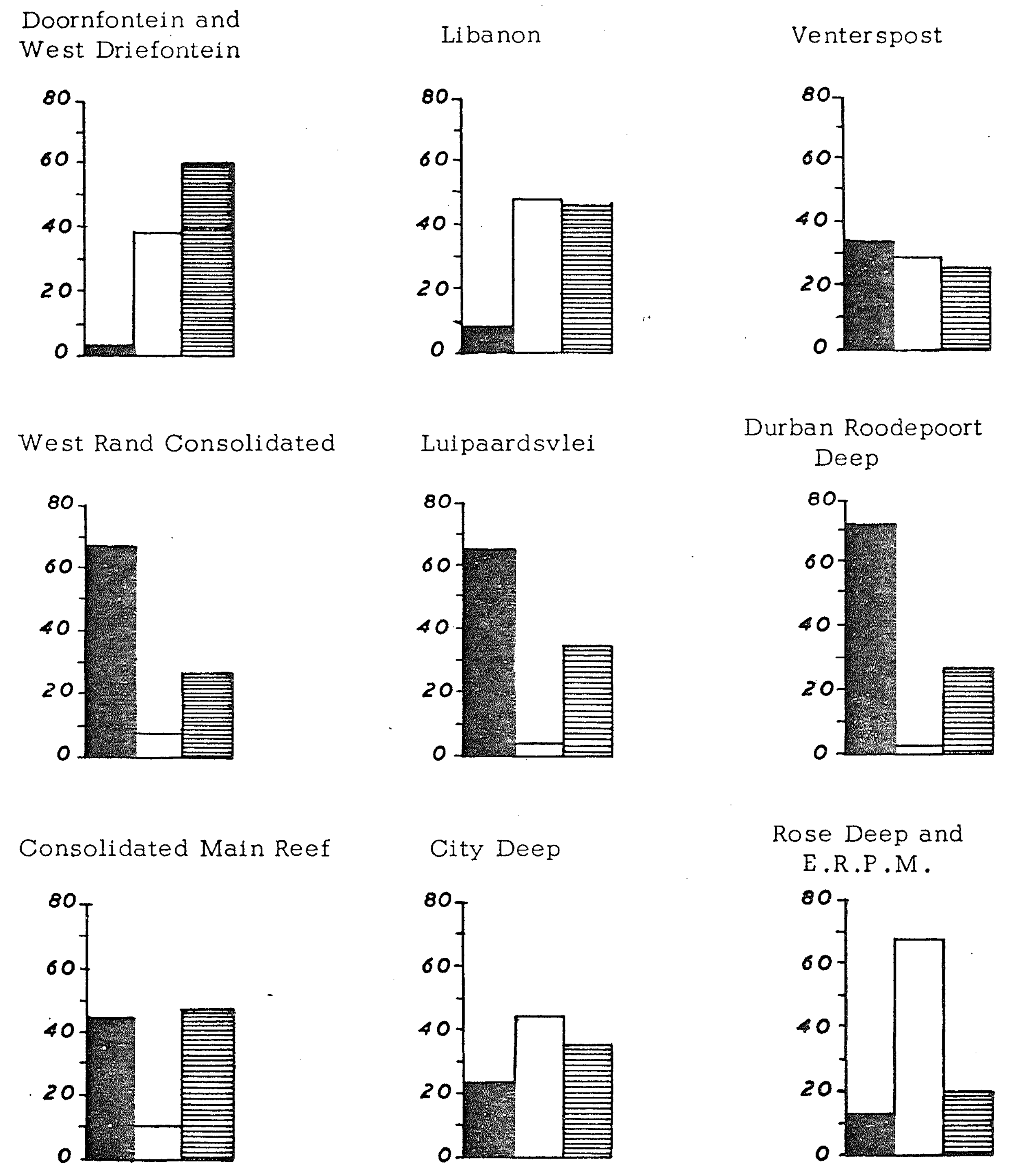


FIG. 3A : Histograms showing the Variations in the Relative Percentages of the Phyllosilicates in the Matrix of the Main Reef. Black represents chloritoid, white, chlorite, and horizontal lines sericite

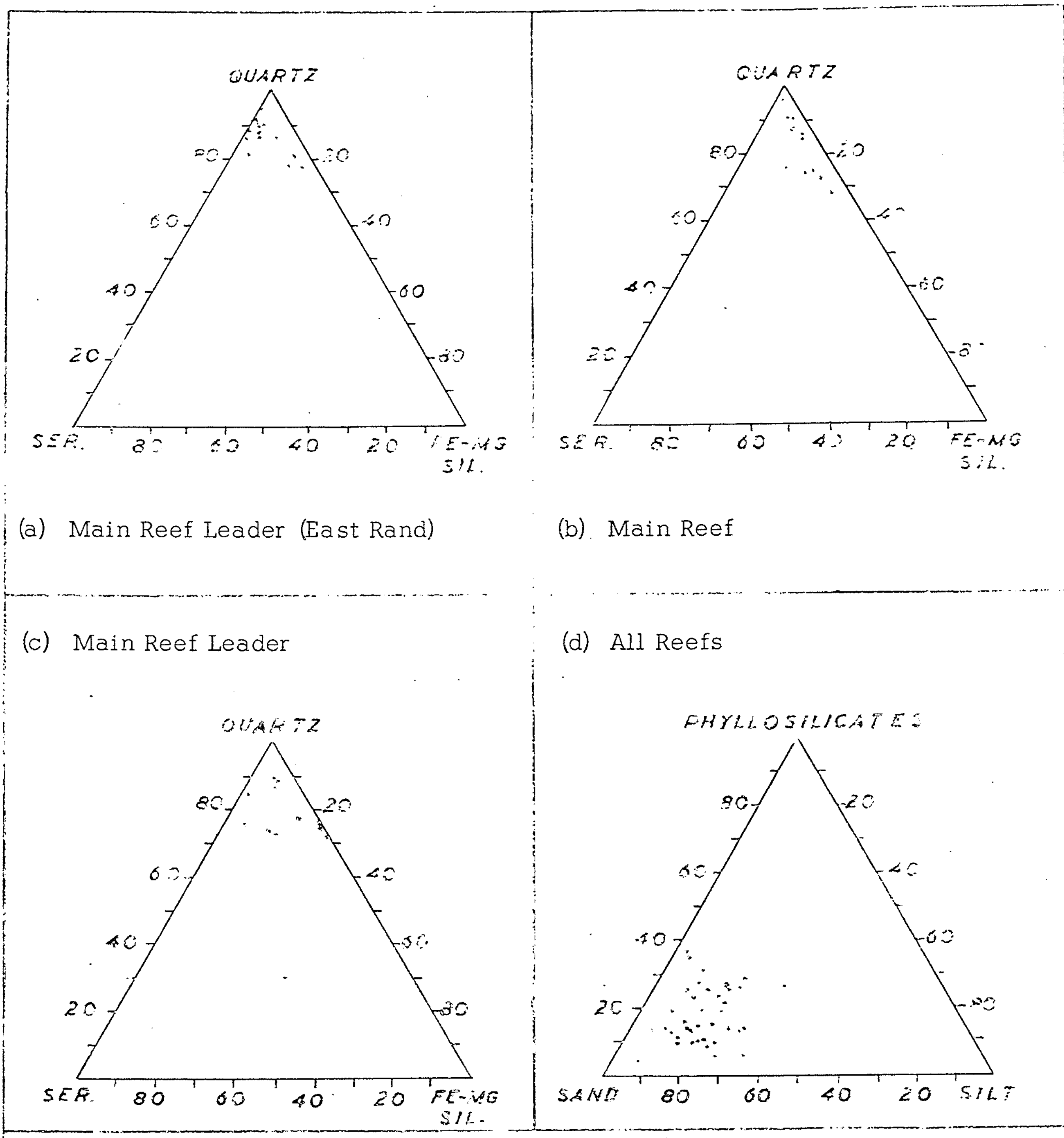


FIG. 4 a, b and c : Ternary Diagrams showing the Relative Percentages of Quartz, Sericite and Iron Magnesian Silicates, portrayed separately for each Reef. ser = sericite FeMg Sils. = Iron Magnesium Silicates

d : Ternary Diagram showing the Relative Percentages of Sand, Silt and Phyllosilicates for all Reef Horizons

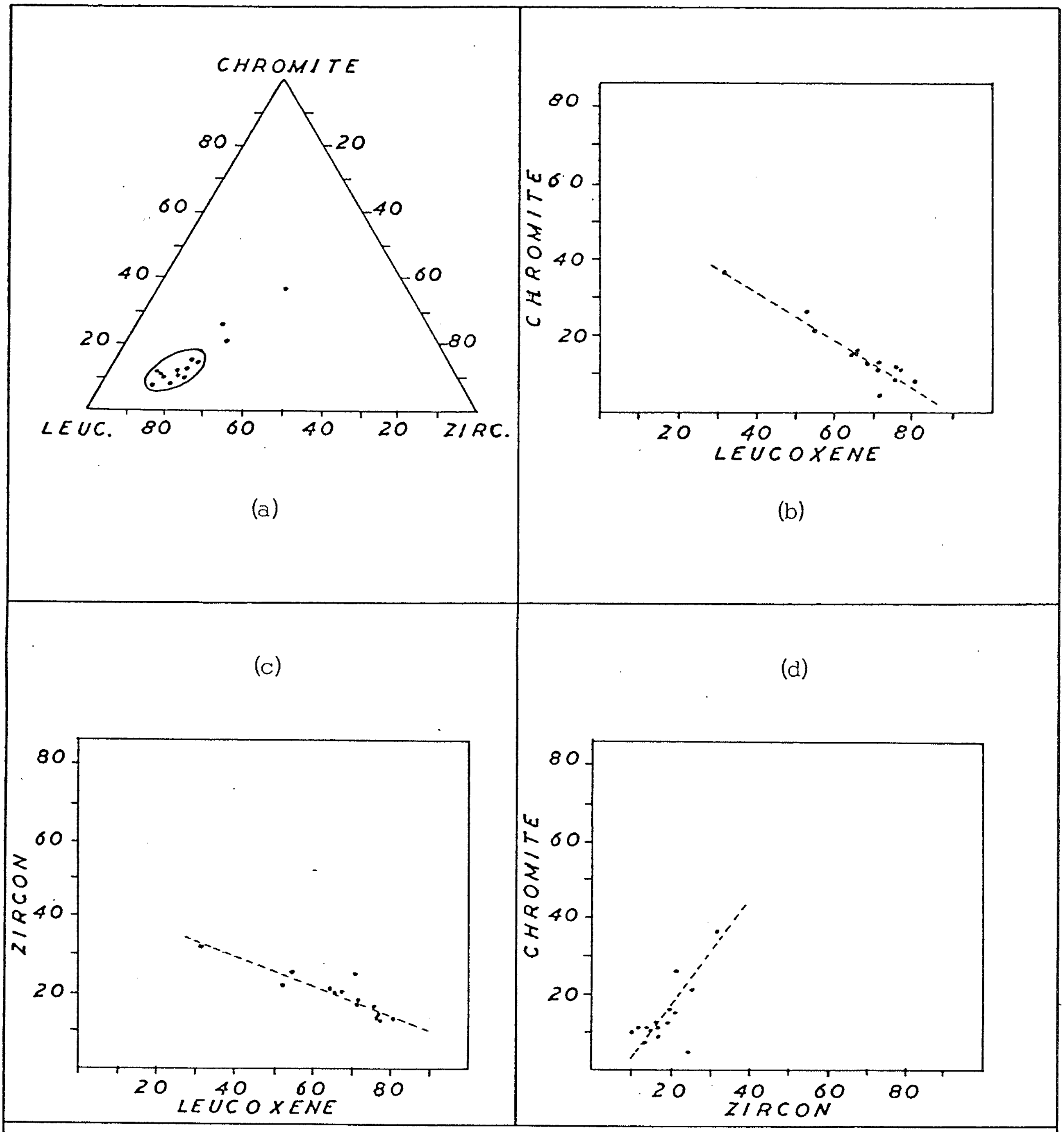


FIG. 5 a : Plot of the Relative Percentages of Chromite, Leucoxene and Zircon within the Main Reef Leader (East Rand)

b, c and d : Plots of chromite/leucoxene, zircon/leucoxene and chromite/zircon respectively in the same Reef

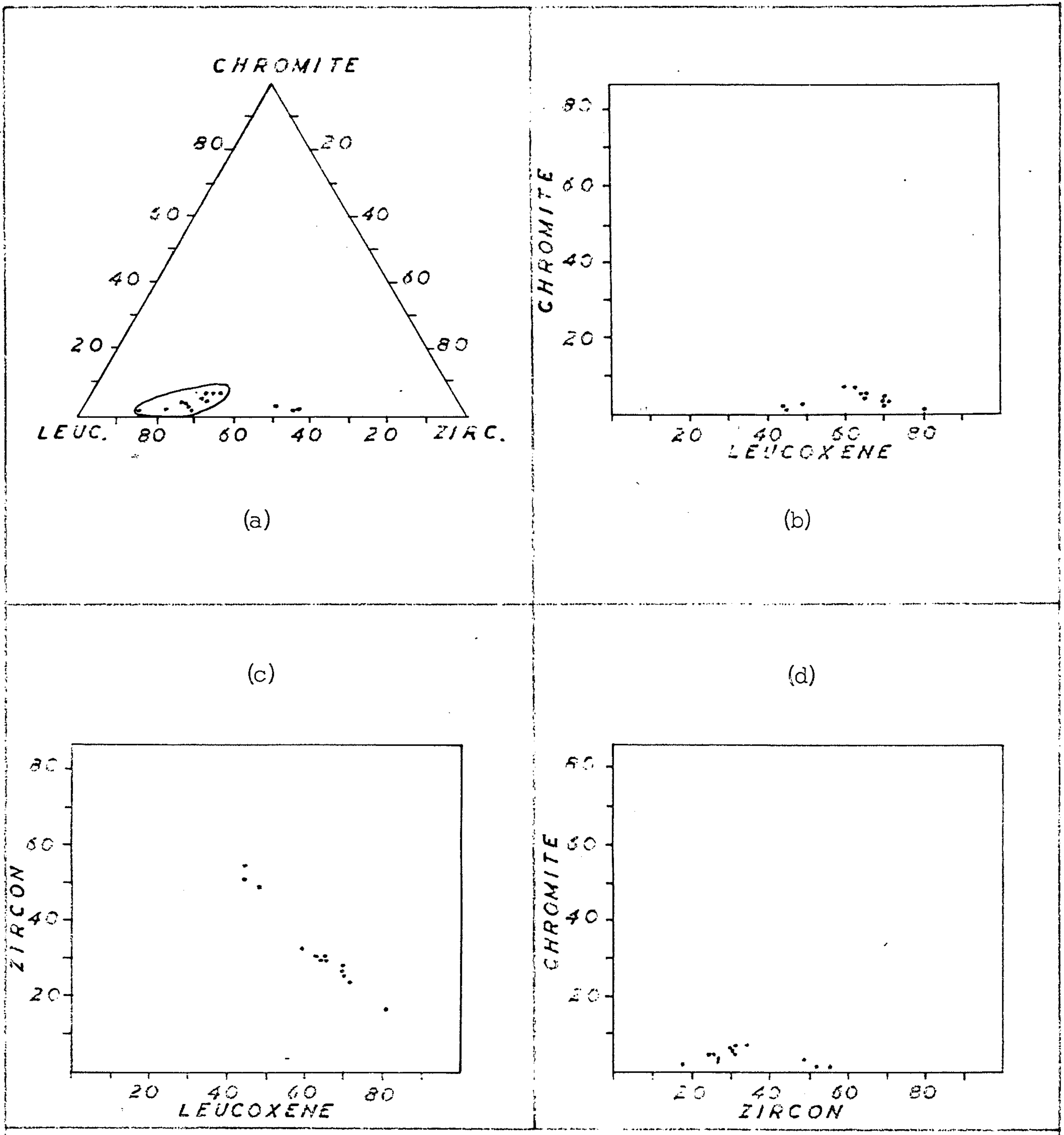


FIG. 6 a : Plot of the Relative Percentages of Chromite, Leucoxene and Zircon within the Main Reef Leader

b, c and d : Plots of Chromite/Leucoxene, Zircon/Leucoxene and Chromite/Zircon respectively in the same Reef

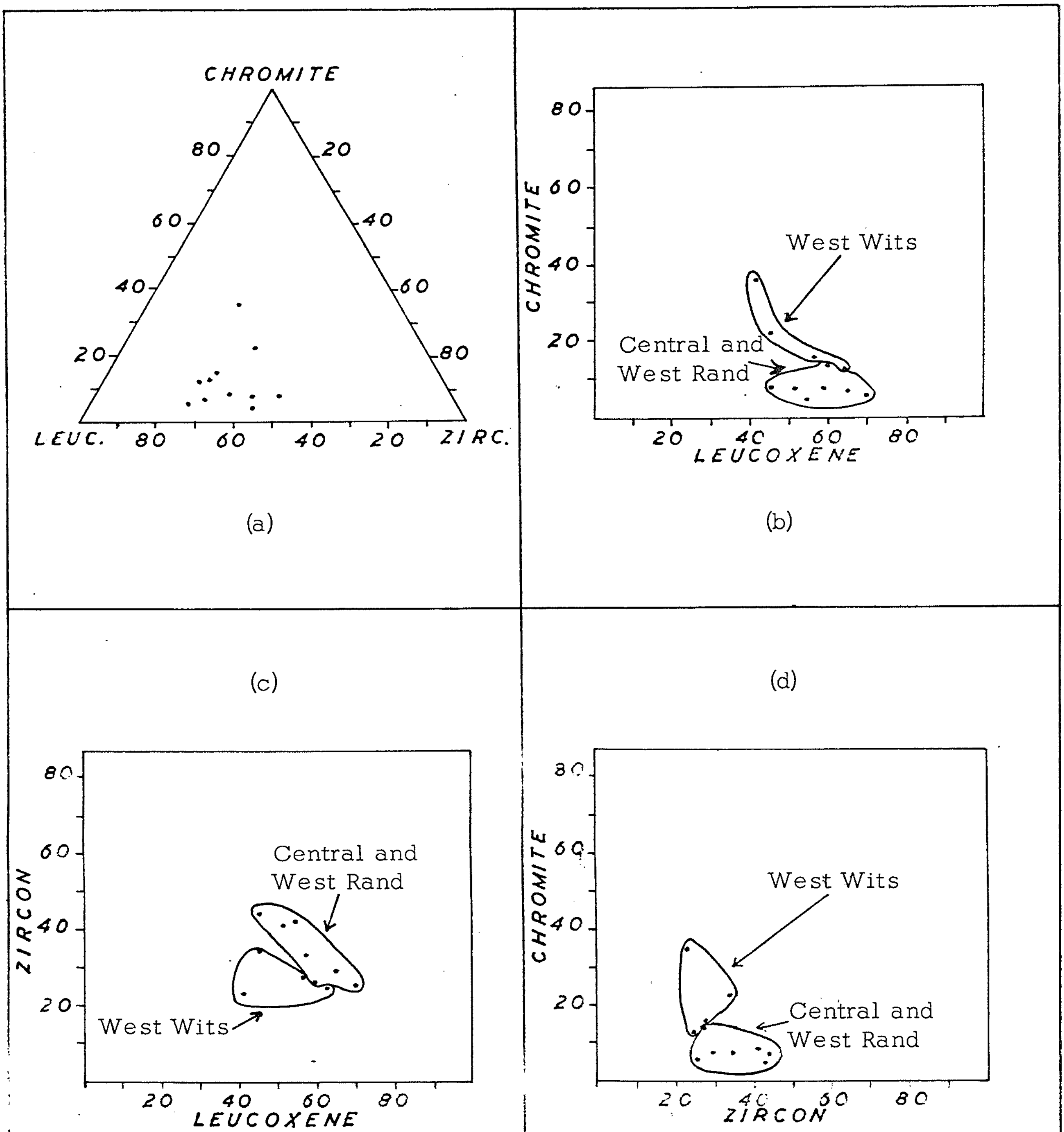
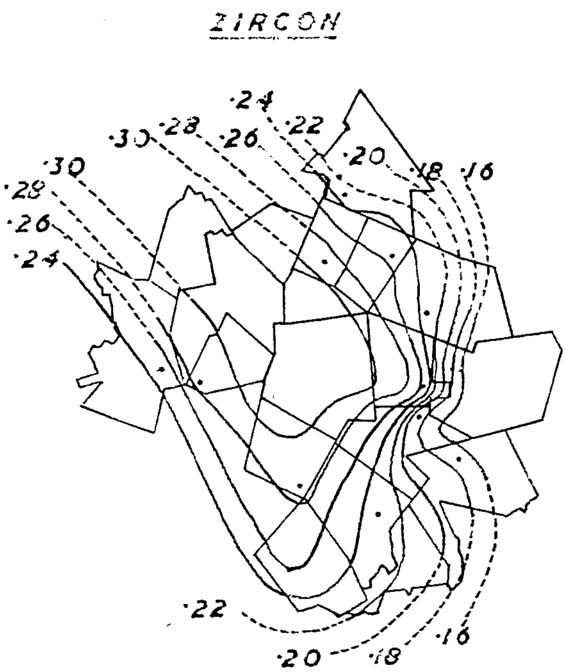
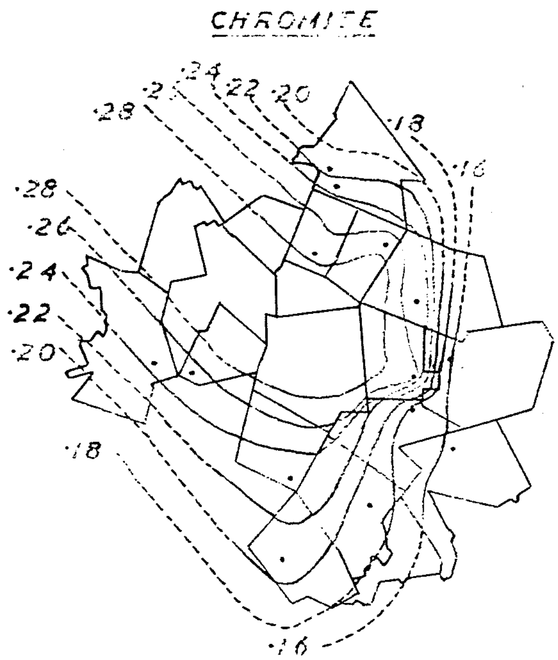


FIG. 7 a : Plot of the Relative Percentages of Chromite, Leucoxene and Zircon within the Main Reef

b, c and d : Plots of Chromite/Leucoxene, Zircon/Leucoxene and Chromite/Zircon respectively in the same Reef. Sub Areas are Indicated on the Diagrams





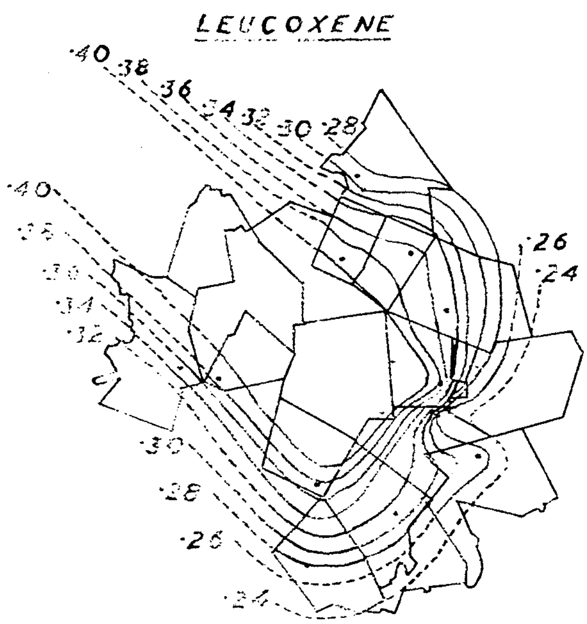
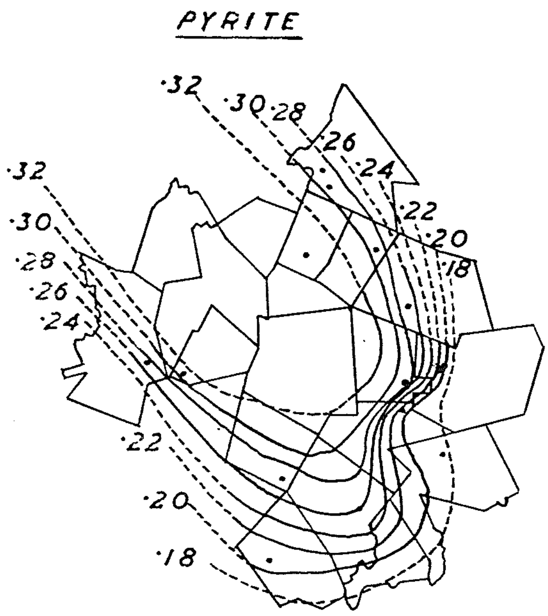
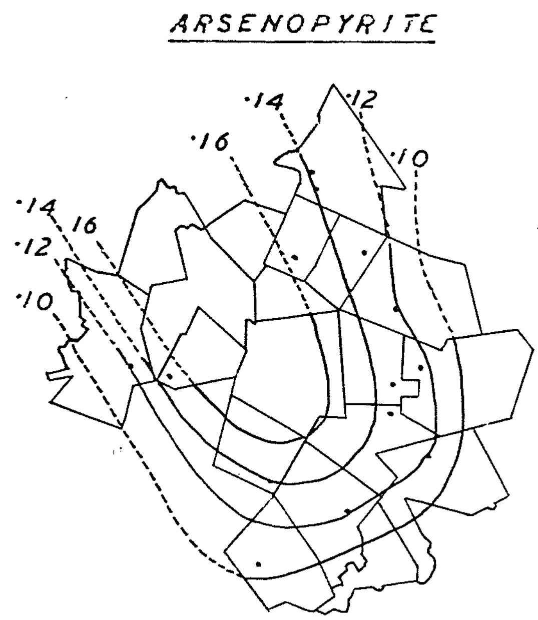


FIG. 8 : Isopleth Maps showing the Lateral Size Variation of Zircon, Chromite and Leucoxene Distributions in the Main Reef Leader of the East Rand Basin. The sizes are given in millimeters and the Isopleths are drawn at .02 mm. intervals. For mine properties see Fig. 1.





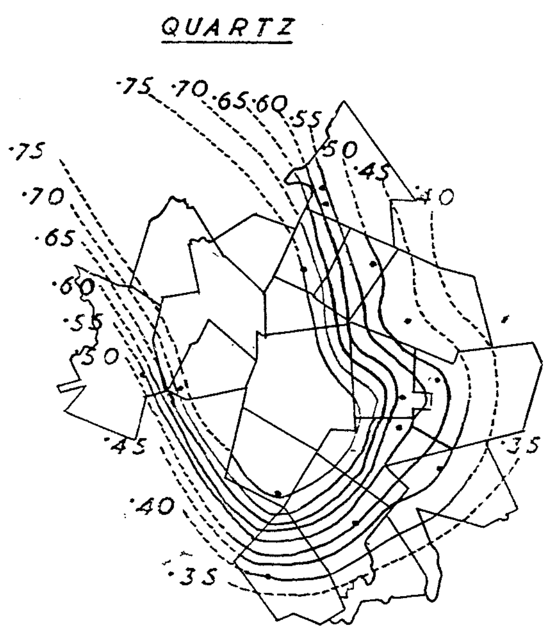


FIG. 9 : Isopleth Maps showing the Lateral Size Variation of Pyrite, Arsenopyrite and Quartz Distribution in the Main Reef Leader of the East Rand Basin. The Isopleths for Arsenopyrite are Drawn According to the Arithmetic Mean Size. The Contour Interval in the case of Pyrite and Arsenopyrite is .02 mm. and in the Case of Quartz .05 mm. For mine properties see Fig. 1.

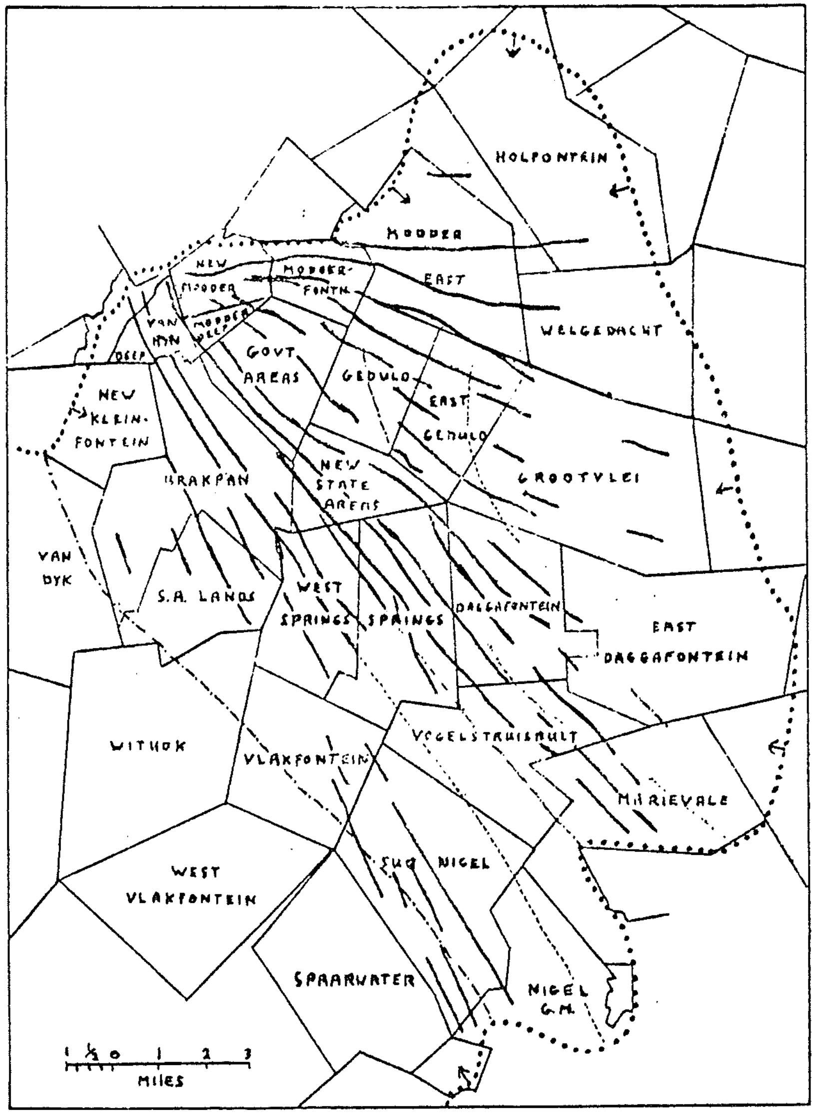


FIG. 10 a : Direction and Position of Major Payshoots within the Main Reef Leader of the East Rand Basin (after Du Toit, 1957)
.........-Synclinal Axes —·—·-Anticlinal Axes

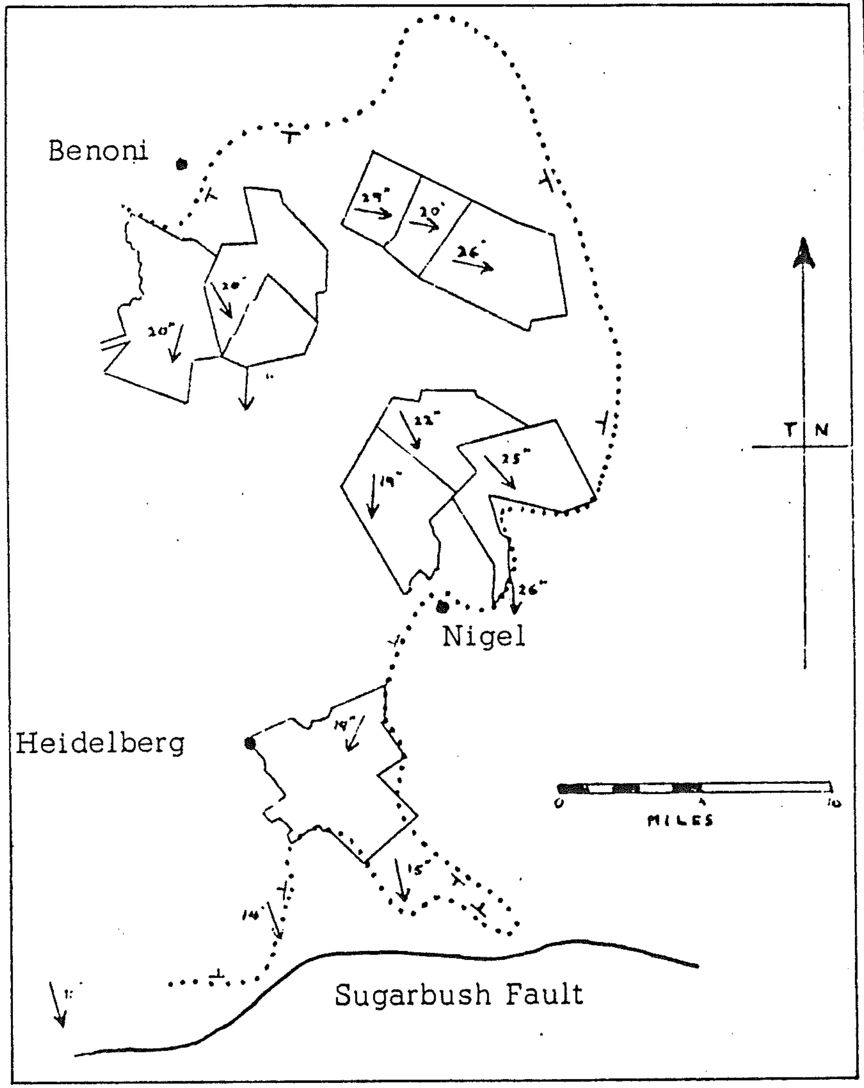
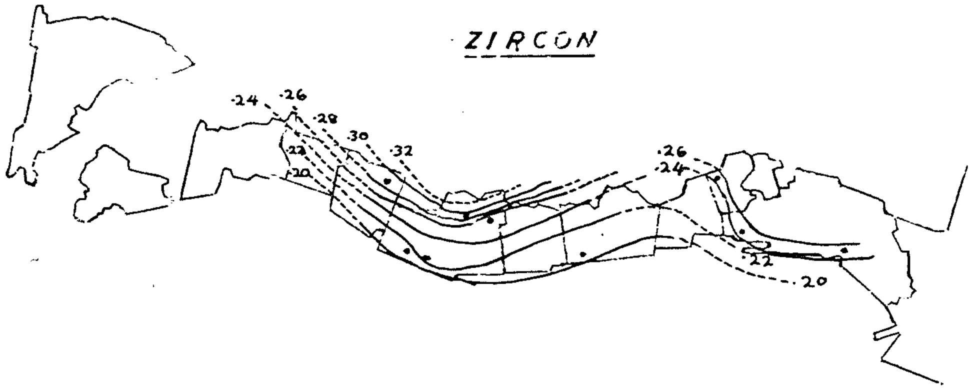
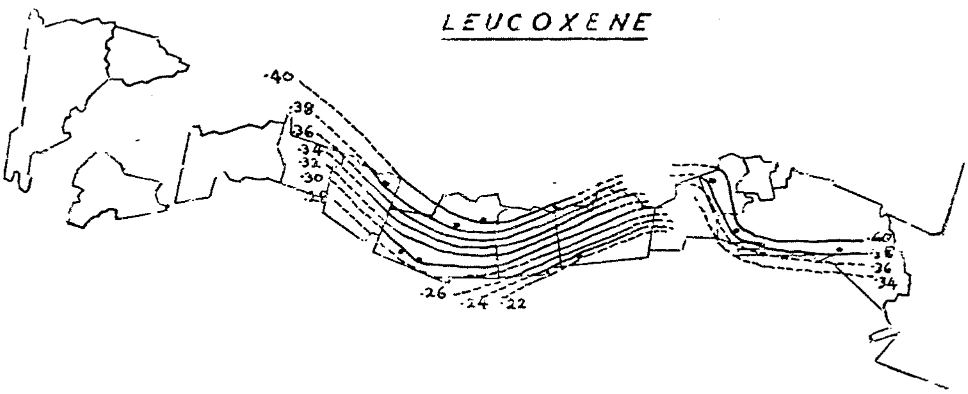
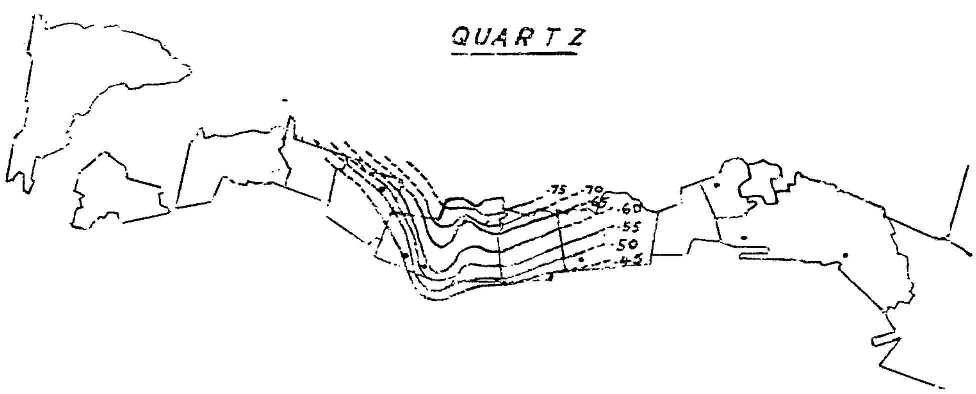


FIG. 10 b : Direction of Cross-bedding in the Main Bird Quartzites of the East Rand Basin. The thickness of cross-bedded units is given adjacent to the arrows. (after Hargraves, 1961)

FIG. 11 : Isopleth Maps showing the Lateral Size Variations of Zircon, Leucoxene and Quartz Distribution in the Main Reef Leader of the Central Rand. The contour interval in the case of Zircon and Leucoxene is .02 mm. and in the case of Quartz .05 mm. The sizes are given in millimeters. For mine properties see Fig. 1.







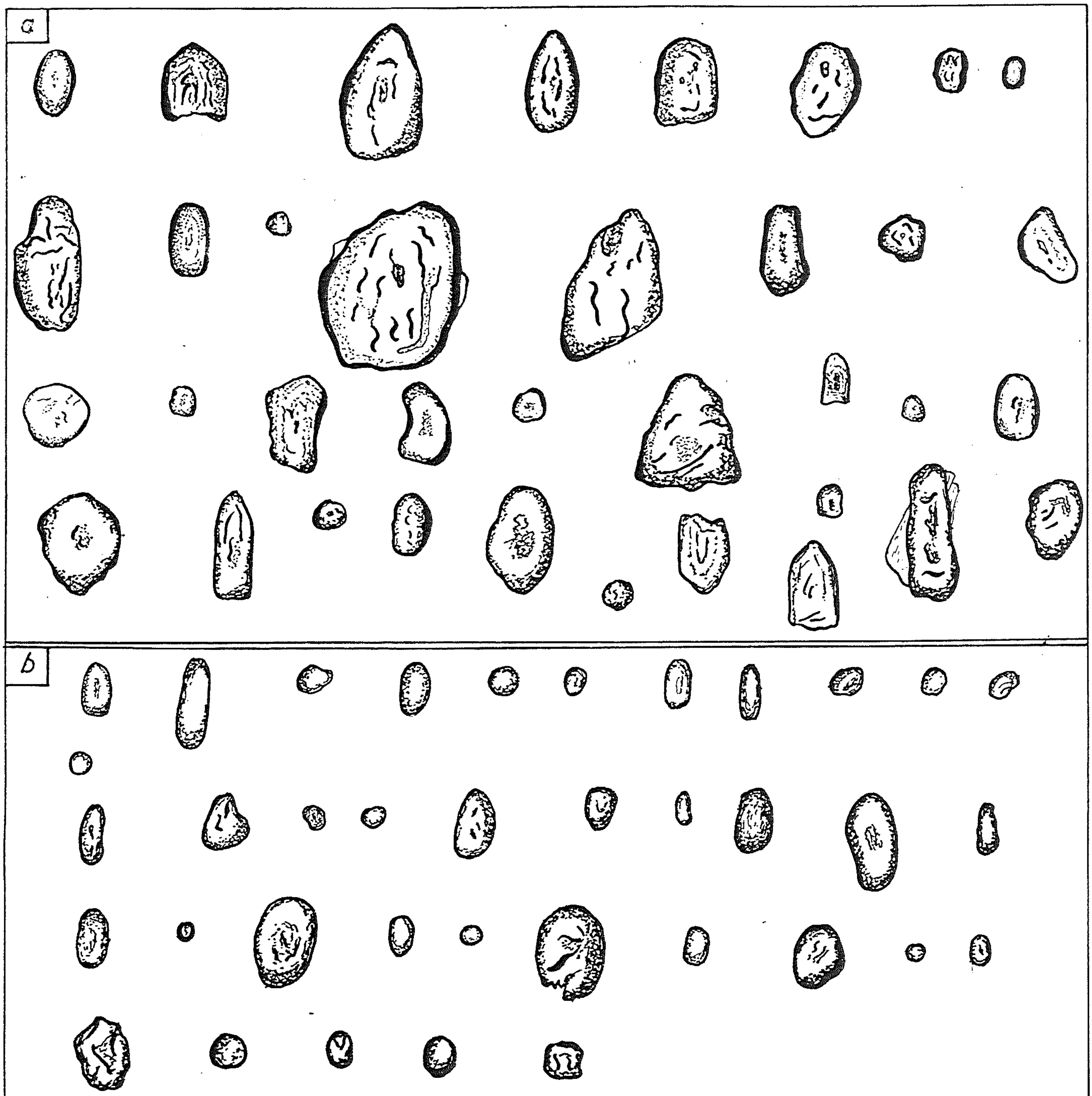
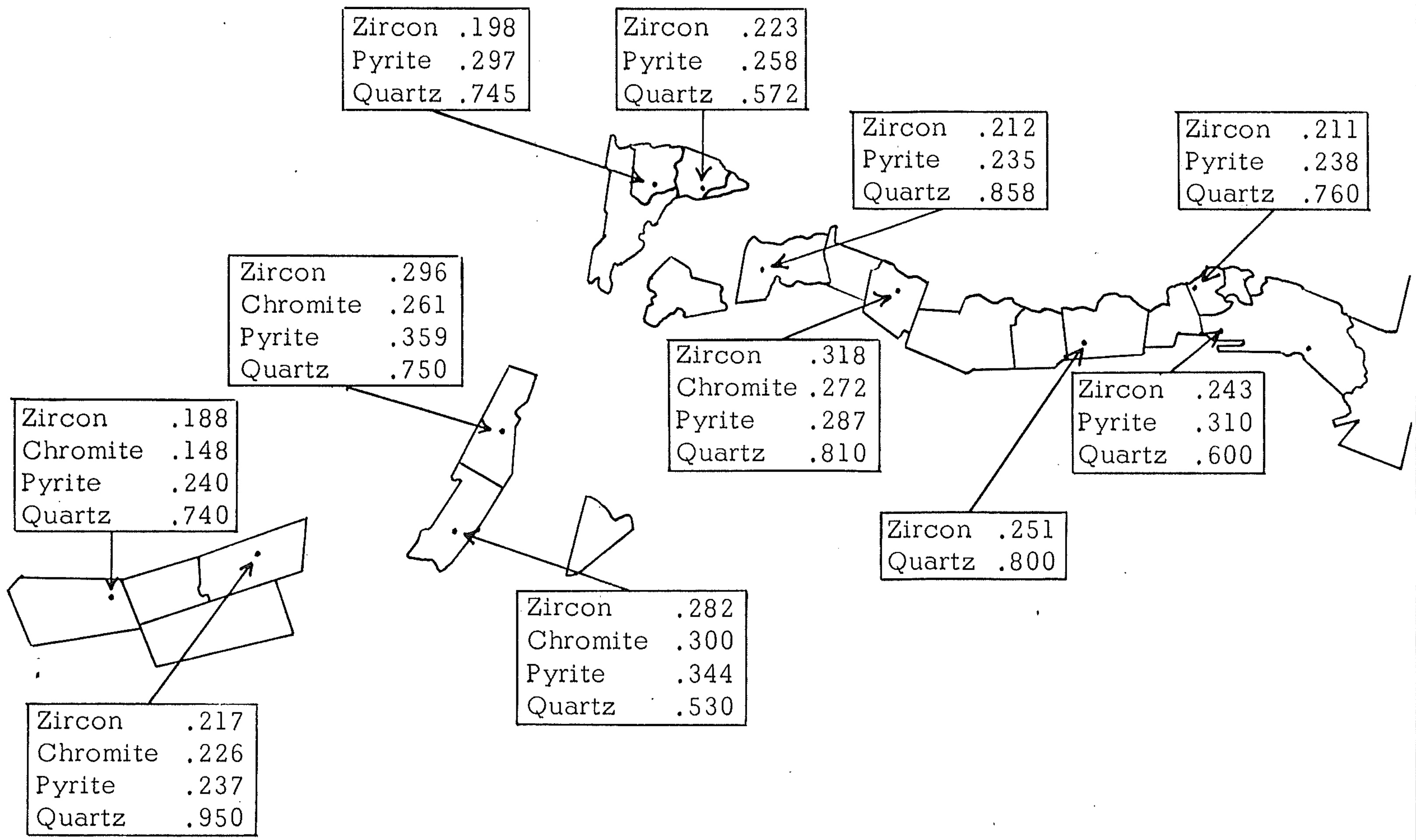


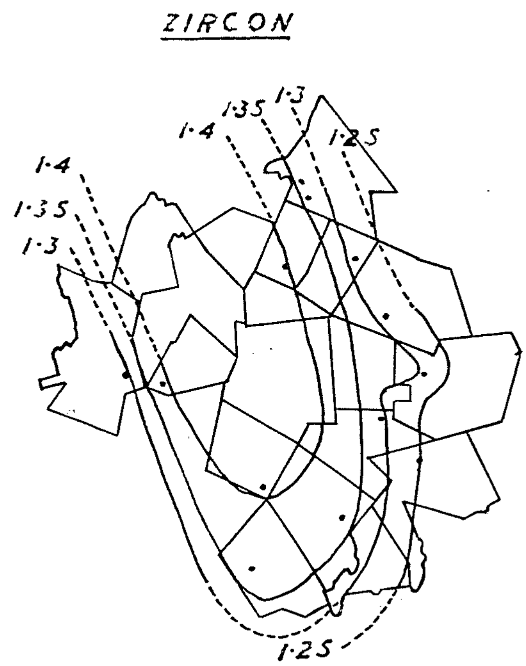
FIG. 12 : Camera Lucida Drawings of 72 Zircon Grains

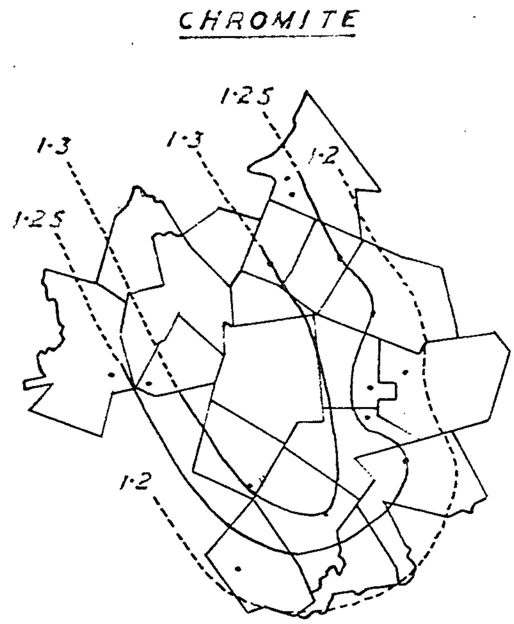
a 36 grains from a sample of Main Reef Leader from Crown Mines, taken at a depth of 3,180 feet. The median grain size of this distribution is .312 mm.,with a sorting coefficient of 1.42

b 36 grains from a sample of Main Reef Leader from Crown Mines taken at a depth of 9,110 feet. The median grain size of this distribution is .211 mm., with a sorting coefficient of 1.17

FIG. 13 : Map showing the Areal Extent of the Main Reef Horizon Investigated. The sizes of individual mineral species are given adjacent to sampling localities. Sizes are given in millimeters. For mine properties see Fig. 1.







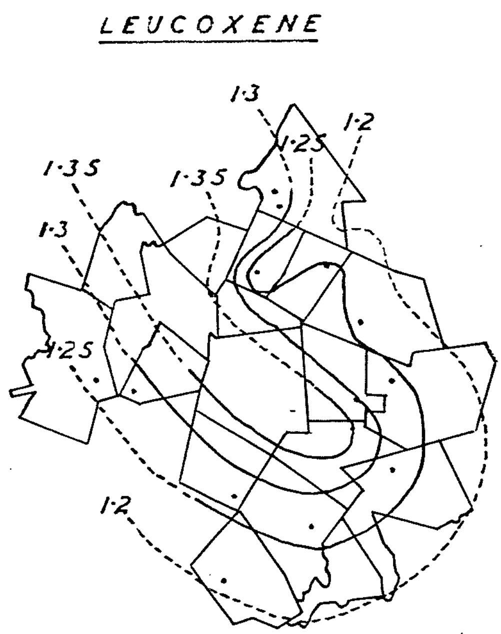
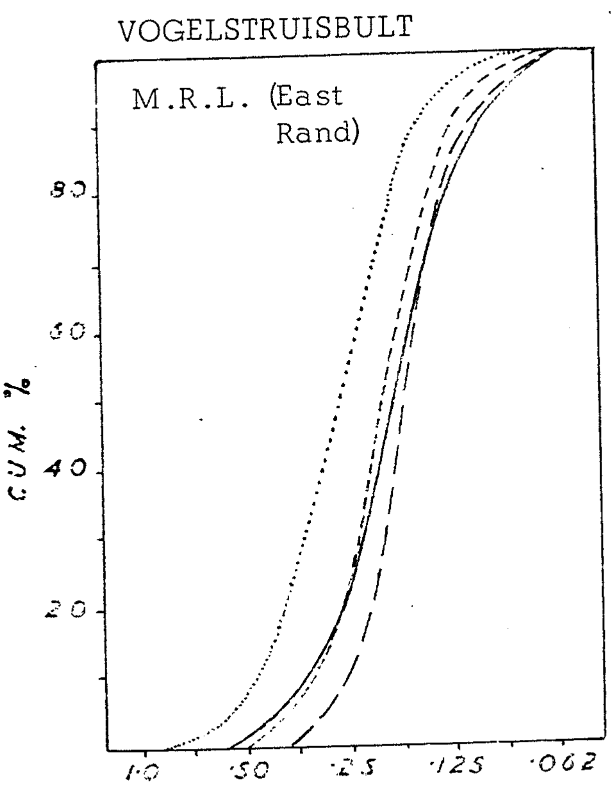
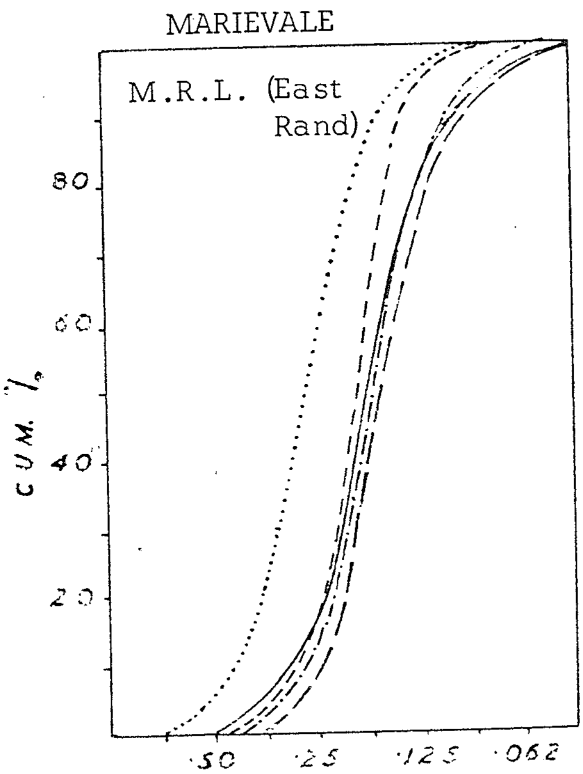


FIG. 14 : Contour Maps showing the Lateral Variations in the Sorting Coefficients (after Trask) of Zircon, Chromite and Leucoxene, in the Main Reef Leader of the East Rand Basin. For mine properties see Fig. 1.





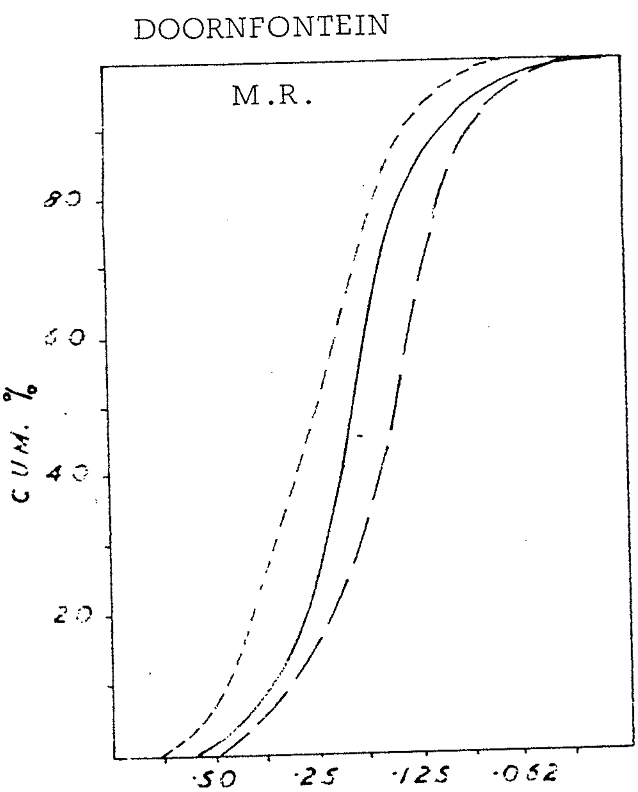
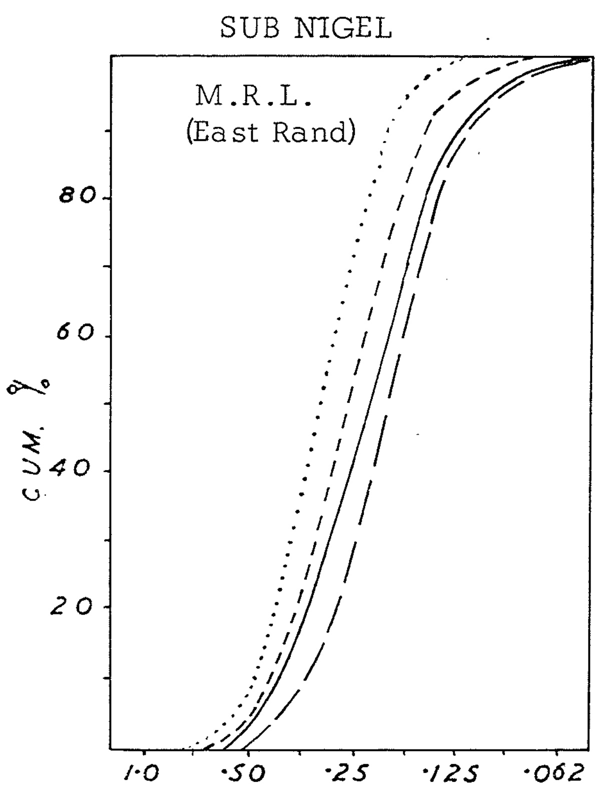
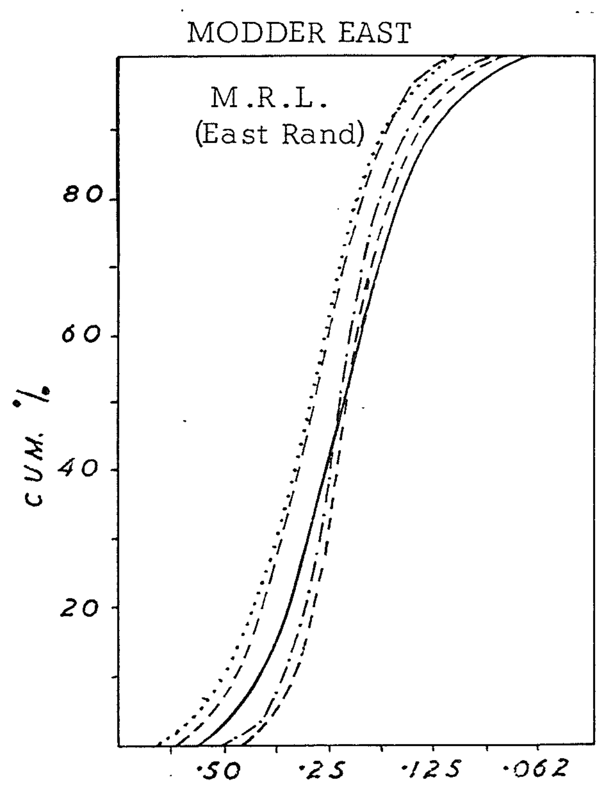


FIG. 15 : Cumulative Curves depicting the Continuous Size Distribution of Various Heavy Mineral Components from the Matrix of the Reefs under Investigation

. . . . Leucoxene
— — — — Pyrite
———— Zircon
—— —— Chromite
—·—·—·— Arsenopyrite





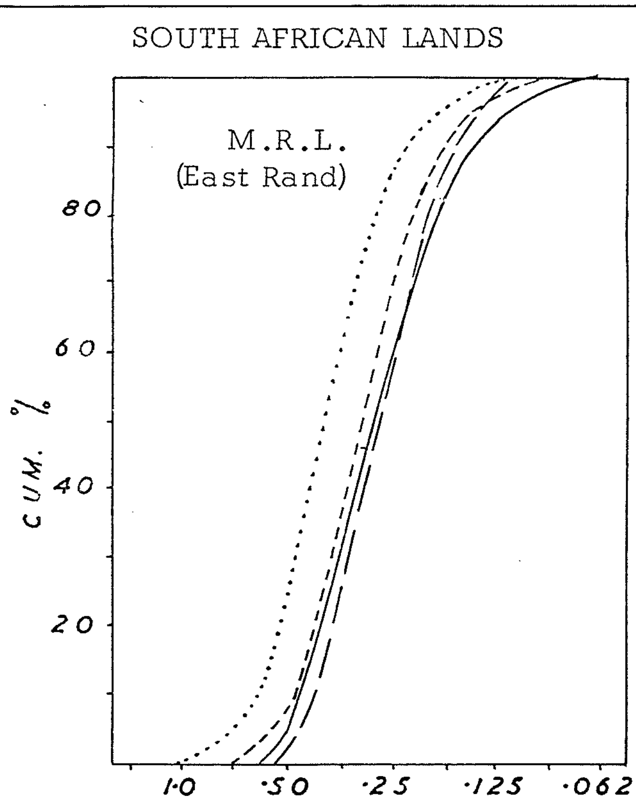


FIG. 16 : Cumulative Curves depicting the Continuous Size Distribution of Various Heavy Mineral Components from the Matrix of the Reefs under Investigation

Leucoxene
Pyrite
Zircon
Chromite
Arsenopyrite

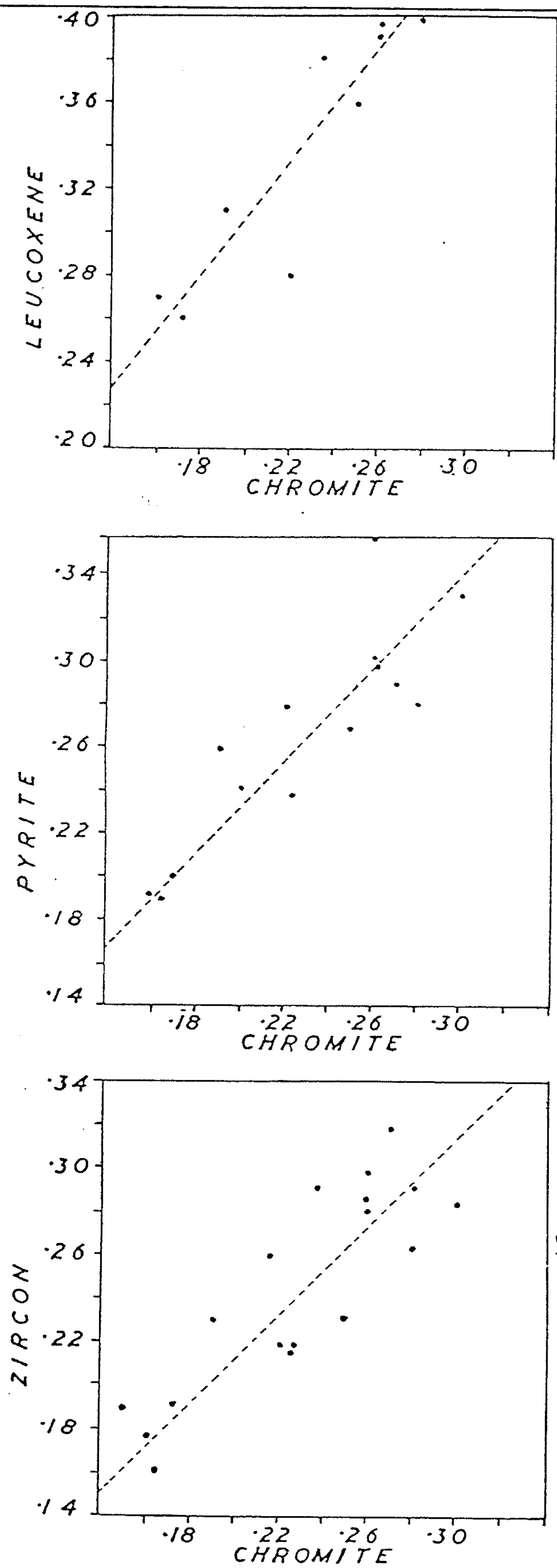


FIG. 17 : Two-Component Scatter Diagrams Obtained by Plotting Various Combinations of Mineral Size against each other.

a : Plot of $\frac{\text{Leucoxene}}{\text{Chromite}}$

Correlation coefficient = .9769

b : Plot of $\frac{\text{Pyrite}}{\text{Chromite}}$

Correlation coefficient = .8160

c : Plot of $\frac{\text{Zircon}}{\text{Chromite}}$

Correlation coefficient = .7995

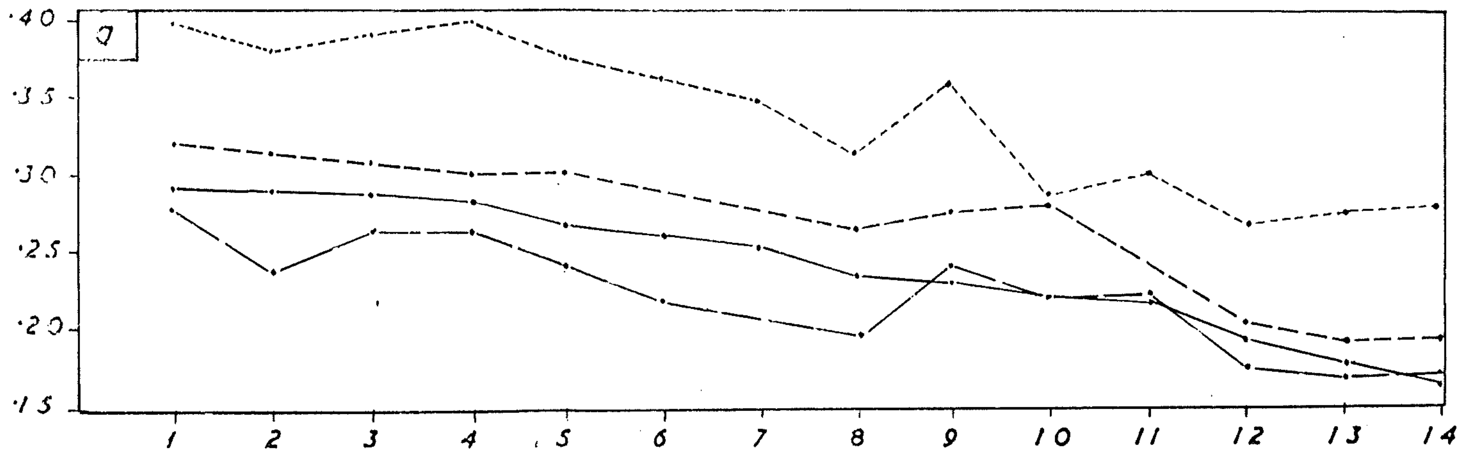
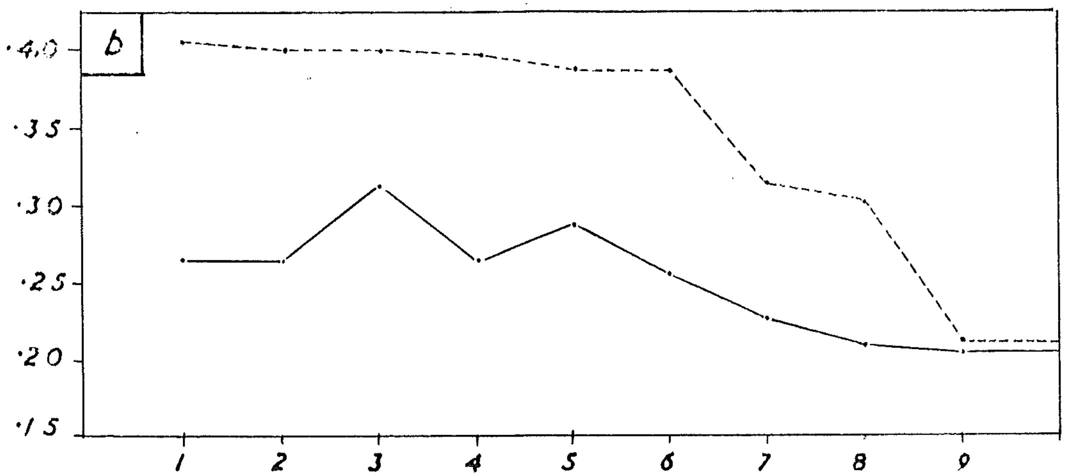
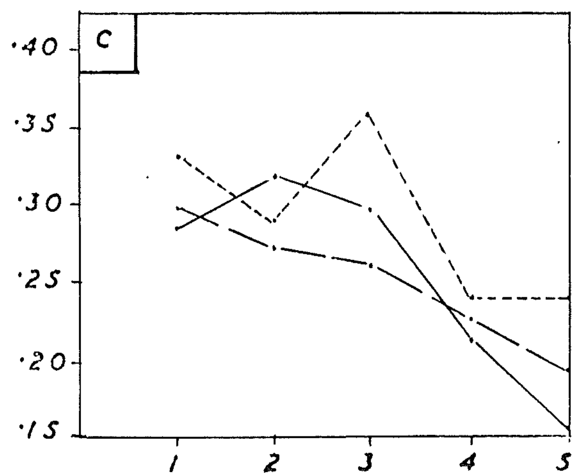


FIG. 18 : Variation in the Median Grain Sizes of Heavy Mineral Components from (a) Main Reef Leader (East Rand), (b) Main Reef Leader, (c) Main Reef.

Symbols used : ———— Zircon : — — — Chromite : -------- Leucoxene : – – – – Pyrite





N.B. : Numbers designate sample localities - See attached sheet.

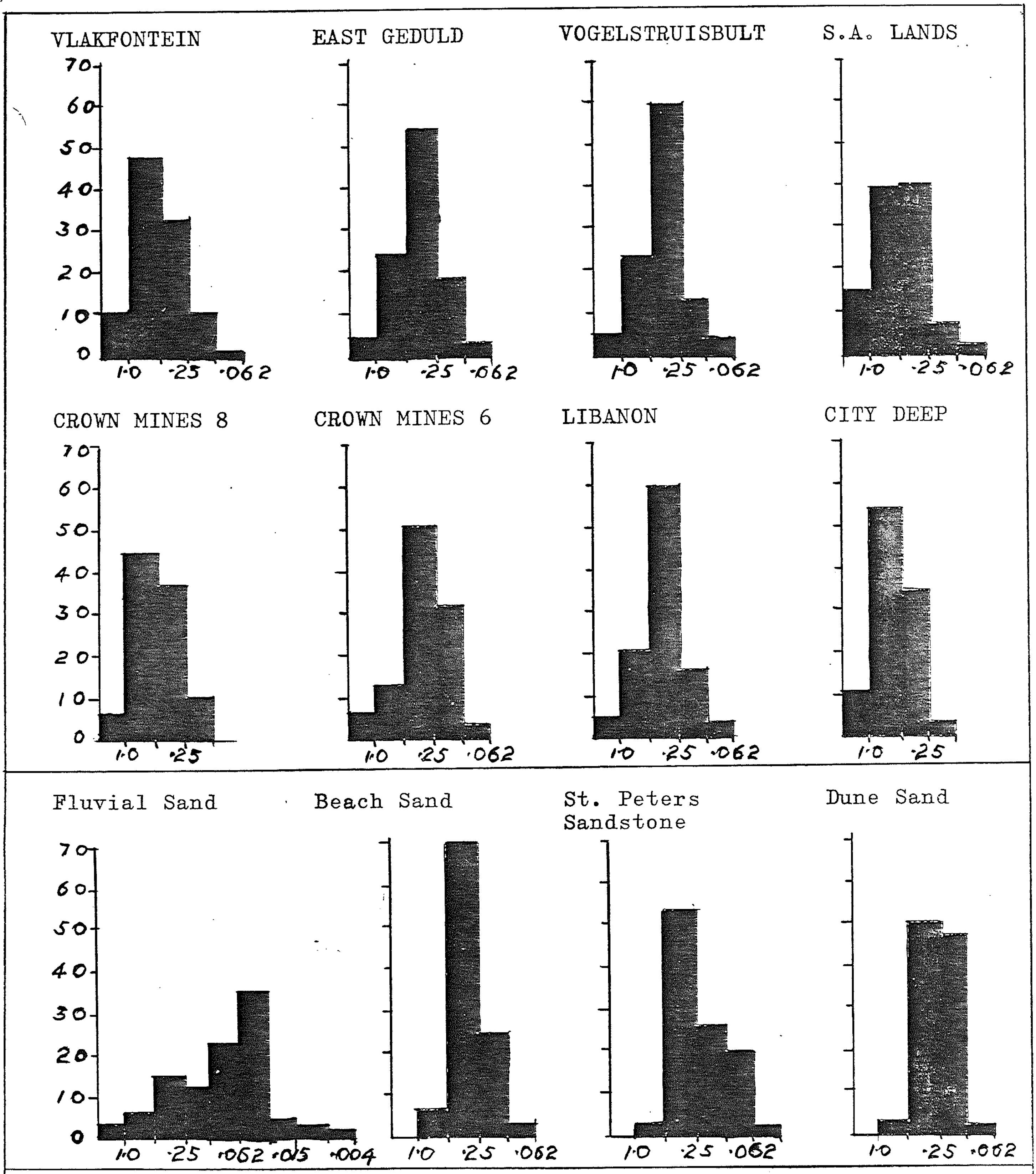


FIG. 19: 8 Histograms representing the Size Distribution of Sand within the Matrix of 8 Different Samples of Reef. The Bottom 4 Histograms represent the Size Distribution of Sand in known present day Deposits, for Comparison (After Weller, 1960)

FIG. 20 : Map of the Area under Investigation showing the Main Structural Features (major synclinal and anticlinal axes as well as major faults). Probable points of entry and direction of transport of reef material have been indicated by arrows. Points of arrows represent approximately the probable points of entry of reef material.