# GEOLOGY AND ORE RESERVE ESTIMATION

OF THE WITWATERSRAND-TYPE GOLD DEPOSITS

WITH SPECIFIC REFERENCE TO THE

WELKOM GOLDFIELD

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Dissertation submitted in partial fulfilment of the requirements for the degree of Master of Science (Mineral Exploration) at Rhodes University.

TR 81 - 14

January, 1981

This dissertation was prepared in accordance with specifications laid down by the University and was completed within a period of ten weeks full-time study.

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# INTRODUCTION

Gold, since before recorded history, has been the archetypal precious metal. For several thousand years it has been the basic currency for trading and in present times it is still the fundamental basis on which the economic stability of nations rests. In addition to its economic value, its malleability, resistance to corrosion and attractive colour have made it the foremost metal used in the manufacture of jewellery. Fully 42% of the 1765 tonnes of gold available to the private sector in 1979 was worked into jewellery with the rest being used for private investment and specialized industrial uses. At an average received price of \$304/t.oz. for 1979 this constitutes a total revenue of 18.9 billion U.S. dollars (Mining Journal, 1980).

South Africa is extremely fortunate in possessing the largest reserves of gold of any country in the world and is thus the world's largest gold producer. In 1975 South Africa was estimated to have 49% of the world's reserves while producing 59% of the world's gold production (van Rensburg and Pretorius, 1977). This imbalance between reserves and production has been fortuitously resolved by the rapidly escalating gold price in recent years, resulting in considerable low grade reserves becoming economically viable. This is exemplified by figures published in World Mining (1980) which show that South Africa's production rate has only increased marginally (5%) from 1977 to 1979 while total reserves have increased by 105%. The increased viability of lower grade ore is reflected by a drop of ore reserve grade from 14.31 g/t to 12.04 g/t.

Gold in South Africa is found either in hydrothermal vein deposits largely restricted to Archean greenstone belts or, far more importantly, in fossil placer deposits in the five Proterozoic basins on the Kaapvaal craton. The majority of gold derived from hydrothermal vein deposits is from deposits situated in the Barberton greenstone belt with lesser amounts coming from the other South African greenstone belts. Vein deposits in other stratigraphic groups in South Africa make a minor and erratic contribution to the total gold production. Important though they may be, the contribution that vein deposits make to South Africa's total gold production is completely overshadowed by that of the fossil placer deposits. The exploitation of these deposits is responsible for over 90% of South Africa's gold production.

Five major Proterozoic basins are preserved on the Kaapvaal craton spanning a time period from 3000 m.y. to 1750 m.y. From oldest to youngest these are the Pongola, Witwatersrand, Ventersdorp, Transvaal and Waterberg sequences. All five appear to have followed a broadly similar evolutionary history but differences in source area, palaeo-ecology and levels of tectonic activity during basin evolution have apparently resulted in the formation and preservation of auriferous placer deposits only in the Pongola, Witwatersrand and Transvaal basins. The Pongola and Witwatersrand deposits are the only true placer deposits, with the Transvaal deposits resulting from the remobilization of low grade protore by tectonic and thermal processes. Gold production from the Witwatersrand sequence exceeds that from the other Proterozoic sequences by almost two orders of magnitude, being 98.5% of the total, up to 1971 (Pretorius, 1976a). Mining activities in areas outside the Witwatersrand sequence have declined in recent times as evidenced by the fact that non-Witwatersrand sources contributed only 1% of total gold production in 1974 (Coetzee, 1976). Recent gold price increases have stimulated a flurry of exploration activity but no discoveries have been made in non-Witwatersrand rocks which would have a significant effect on this proportion. Thus it is that a single sequence of rocks, the Witwatersrand sequence, contributed 59% of the world's gold production in 1979.

In a South African context gold revenue in 1979 constituted 60% of the total mineral revenue. This dominant role of gold in South Africa's mineral economy makes it imperative that its gold reserves are effectively evaluated and exploited. A complimentary factor is the need for increasingly efficient evaluation techniques to cater for lowering cut off grades resulting from the rapid escalation of the gold price. In comparison with the technological advances in other aspects of the gold mining industry the evaluation techniques employed on Witwatersrand-type gold deposits have improved little over the years. It is only relatively recently that geostatistical techniques have been developed and applied to

these deposits. The use of these techniques are not as widespread as they might be, because it has yet to be resolved whether they provide batter grade estimation than the conventional methods. In addition highly sophisticated computer hardware and software are required to process data by geostatistical techniques. Irrespective of whether conventional or geostatistical methods are employed, the data derived from these methods must be interpreted in the light of the geological characteristics of the orebody in question. If this is not the case then seriously erroneous conclusions may be arrived at, resulting in incorrect financial decisions being made regarding the ore deposit under consideration. This dissertation will attempt to review the geological features of Witwatersrand-type gold deposits, the various ore reserve evaluation techniques and their applicability in the light of the geological characteristics of these deposits, with special reference to the Steyn Reef at the Welkom Mine, Welkom, Orange Free State.

### WITWATERSRAND BASIN

### Introduction

The considerable economic importance of the Witwatersrand sequence of rocks is clearly without question. In the past decade or so the tendency to regard ore deposits as exotic entities largely unrelated to the geological evolution of their host rocks has been superseded by the view that they are an integral and logical part of this evolution. Current thought on the evolution of the Witwatersrand basin and the formation of the gold deposits supports the view that they are inextricably linked and that the gold deposits are a natural result of a favourable combination of suitable source area, transport mechanism and depositional environment. Thus any discussion concerning the Witwatersrand gold deposits must be prefaced by a consideration of the evolution of the basin and the characteristics of its sediment infill.

# Basin Morphology and Structure

The Witwatersrand basin has a curved elliptical shape, oriented northeast-southwest and is situated approximately in the centre of the Kaapvaal craton (Figure 1). The exact dimensions and shape of the basin are still uncertain because of widespread younger cover with resultant paucity of outcrop, but it is probably of the order of 350 km. long by 200 km. wide (Figure 2). Its depositional axis strikes northeast and it has been folded around a northwest axis. The basin and its margins are punctuated by a number of granite domes which are believed to have played an important part in the basin evolution and localization of the gold fields.



FIG. 1. The main crustal provinces of southern Africa and the locations of some of the better known geological formations (Archean greenstone belts, Great Dyke, Bushveld Complex, and Witwatersrand Basin).

From Pretorius and Maske, 1976.



Fig. 2. The Witwatersrand Basin (after Pretorius 1974).

From Truswell, 1977.

In plan the basin displays a moderately good symmetry but inspection of the isopachs of the upper and lower Witwatersrand rocks (Figure 3) shows a clearly asymmetric basin shape in section, with the northwestern side of the basin being the steeper of the two. The isopachs also clearly show that the basin decreased in size during its evolution. This size decrease is also markedly asymmetric with strong offlap occurring along the northwestern margin and weak onlap on the southeastern margin of the basin, but note that, in spite of this assymetry, the depositional axis has remained essentially stationary. It is of considerable economic interest that both ends of the basin are still open and have yet to be defined. Basin asymmetry is further reflected by the nature of the basin edges. The northwestern edge is characterised by major normal strike faults while the southeastern margin is defined by a lateral pinching-out of the strata. The gradients of the palaeoslopes provide useful evidence in elucidating the evolution of the basin and also demonstrate the basin's asymmetry. During lower Witwatersrand sedimentation the slopes were respectively 1:25 and 1:30 on the northwestern and southeastern sides of the basin while during upper Witwatersrand times the slopes were 1:20 and 1:40 respectively. Thus it can be seen that higher energy conditions prevailed during upper Witwatersrand times especially on the northwestern edge of the basin. This has important



economic implications, as will be discussed later (Pretorius, 1976a).

Fig. 3. Isopach map for the Witwatersrand. A. Lower Witwatersrand. B. Upper Witwatersrand (after Pretorius 1974).

From Truswell, 1977.

# Stratigraphy

The Witwatersrand System sensu stricto is a thick sequence of shales, quartzites and conglomerates which have undergone low grade regional metamorphism and are divided into a lower, argillaceous unit and an upper, more arenaceous unit. This system is underlain by the Dominion Reef "System" and is in turn overlain by the Ventersdorp System. These sequences are separated by locally pronounced unconformities, but these are often not detectable and no more marked than those occurring within the Witwatersrand System itself. Universal boundaries between the sequences have yet to be defined, and recent suggestion is that the Dominion Reef sequence is merely an early, localised volcanic phase of the Witwatersrand System (Truswell, 1977), and the Klipriviersberg volcanics are a terminal phase of the upper Witwatersrand sequence (Pretorius, 1976b). Whatever the true situation is, these three sequences follow each other closely in geological time and are considered to represent rocks deposited during a single major geological cycle. The Witwatersrand sequence is not fully developed at any one locality in the basin but utilising data from type areas for the various members of the sequence, Pretorius (1976b) compiled the composite stratigraphic column shown in Table 1.

#### TABLE 1

Composite stratigraphical thickness and ratios of Witwatersrand Sequence from type areas of development

Group	Total (m)	Volcanics (m)	Quartzites (m)	Shales (m)	Sand/shale ratio	Volcanics/ sediments ratio
Klipriviersberg	3,050	2,740	130	180	0.7	8.8
Kimberley-Elsburg	1,670	0	1,640	30	54.7	0.0
Main-Bird	1,490	300	1,010	180	5.6	0.3
Jeppestown	1,380	420	410	550	0.8	0.4
Government	1,970	0	1,240	730	1.7	0.0
Hospital Hill	1,620	0	610	1,010	0.6	0.0
Dominion	2,720	2,650	60	10	6.0	37.9
Klipriviersberg	3,050	2,740	130	180	0.7	8.8
Upper Witwatersrand	3,160	300	2,650	210	12.6	0.1
Lower Witwatersrand	4,970	420	2,260	2,290	1.0	0.1
Dominion	2,720	2,650	60	10	6.0	37.9
Witwatersrand	13,900	6,100	5,100	2,690	1.9	0.8

From Pretorius, 1976.

## Dominion Reef Sequence

The Dominion Reef sequence of rocks is largely restricted to the western edge of the Witwatersrand basin in the Ventersdorp-Klerksdorp area. It consists largely of acid to intermediate volcanics with subordinate clastic and volcano-clastic sediments and attains a maximum thickness of 2650 m. Minor conglomerate horizons are auriferous and have been sporadically worked in the past.

#### Lower Witwatersrand Sequence

Division of the Witwatersrand sequence of rocks is based on the relative proportions of arenaceous to argillaceous rocks. Similarly the subdivisions of the lower Witwatersrand are based on the same criteria. The Hospital Hill and Jeppestown sequences are dominated by argillaceous units while the Government Reef sequence has a preponderance of arenaceous units. Work by Eriksson et al. (1979) shows that the Hospital Hill sequence was deposited in a subtidal environment and it is likely that the majority of the lower Witwatersrand was deposited under shallow marine conditions. Auriferous conglomerates are present in the Government Reef sequence at the base of the Jeppestown sequence but these are a very minor component of the lower Witwatersrand and are unimportant gold producers relative to the upper Witwatersrand reefs. The lower Witwatersrand sequence as a whole shows a marked consistency with individual marker horizons being identifiable in the different parts of the basin, allowing confident correlation from one area to another. Of particular interest is the presence of three magnetic horizons; the Water Tower Slates and Speckled Bed in the Hospital Hill sequence and the Coronation Shales in the Government Reefs sequence. Detection of these horizons by magnetometer surveys followed by straightforward stratigraphic extrapolation to locate auriferous horizons in the upper Witwatersrand played an important part in the development of the West Wits area. In the Welkom goldfield magnetometer surveys also played a significant role in exploration although their value was somewhat reduced by the complicated structure.

## Upper Witwatersrand Sequence

The upper Witwatersrand is the storehouse of the majority of the treasures in the Witwatersrand System, containing 75% of the total number of auriferous reefs exploited in the Witwatersrand sequence. Pretorius (1976b) uses the number of mines exploiting any particular reef zone as a measure of its importance. Using this criterion some 95% of all the mines exploit reefs in the upper Witwatersrand rocks. In spite of the great importance of the Witwatersrand gold reefs in world terms it is at once sobering and encouraging to note that the exploited auriferous reefs constitute only 0.2% of the total stratigraphy. The upper Witwatersrand is dominantly composed of quartzites with numerous intercalated conglomerates. The only significant argillaceous unit present is the Kimberly Shale, the top of which is arbitrarily taken as the boundary between the Main-Bird unit and the Kimberley-Elsburg unit which overlies it. This shale unit is the only consistent marker which can be correlated from goldfield to goldfield. The general character of the major subdivisions of the lower Witwatersrand sequence is similar in all the goldfields but individual units can only tenuously be correlated between adjacent goldfields.

The southeastern margin of the Witwatersrand basin is entirely obscured by younger sequences, as a result little is known of it and even less has appeared in print. The following discussion will thus be confined to the considerably better known northwestern margin. The upper Witwatersrand sequence has a general tendency to coarsen upwards. Pretorius (1976b) notes that the conglomeratic zones become thicker and more closely spaced stratigraphically upwards and points out that this is indicative of regressive conditions, supporting the view point that the basin was characterised by progressively increasing instability as it evolved. The sequence is characterised by cyclic sedimentary units each of which rest on an unconformity or a disconformity. The cycles are usually initiated by the deposition of a basal conglomerate which passes upwards into quartzites. One or more minor cycles with basal conglomerates usually occur within each major cycle. Shales are usually conspicuous by their absence in the cycles except for the Bird Reef cycle which is terminated by the Kimberley Shale.

Thus within the overall coarsening upward sequence there are a number of fining upward cycles. In addition to fining upwards, each cycle also displays a lateral decrease in grain size into the basin with conglomerates passing into quartzites and quartzites passing into shales.

# Nature of the auriferous reefs

The most widely exploited auriferous reefs in the Witwatersrand sequence are the basal conglomerates of the sedimentary cycles. However the occurrence of a conglomerate horizon does not ensure the presence of gold and conversely, especially with the present high gold price, non-conglomeratic horizons may be auriferous. The best developed and richest reefs in terms of total gold content are still those where the gold occurs in the matrix of mature oligomictic conglomerates. As new goldfields are opened up other horizons of gold concentration are becoming more important. Pretorius (1976b) lists these as being:

- 1) pyritic sands which usually fill erosion channels,
- 2) sands in planes of unconformities,
- 3) muds on planes of unconformities,
- 4) carbon seams developed along planes of unconformities.

Irrespective of the nature of the host lithology the association with planes of unconformity or disconformity is ubiquitous, often intimately related to erosion channel features. In all these different horizons of gold concentration the majority of the gold is found at or near the basal plane of discontinuity. An important characteristic of these horizons is their greater maturity relative to their bounding rocks. It is important to note that the typical conglomeratic reef often passes laterally, in a basinward direction, into one or other of the other types of reef. This point will be more fully discussed in a later section. This lateral facies correlation is not complimented by a correlation of specific reefs from goldfield to goldfield. In the past such correlations have been attempted and in many cases were apparently successful, but more recently indications are that this is a result of contemporaneous similarities in the tectonic histories of adjacent goldfields rather than a true, direct correlation.

Uranium in the form of uraninite, is the only other major ore metal present in the auriferous reefs. It is intimately associated with the gold mineralization but does display significant differences in distribution relative to gold. Different reefs will be characterised by different U/Au rations. For example the Main group of reefs is characterised by low ratios in the vicinity of 10 while in the Bird Reefs the ratios are considerably higher and can attain values of 769. In the Bird group there is also a positive correlation between reef thickness and ratio (Minter, 1972, in Pretorius, 1976b). This is related to the fact that gold tends to be concentrated at the base of a reef and as such no marked correlation between gold content and reef width exists, while uranium is normally evenly distributed throughout the reef giving a strong positive correlation between reef width and uranium content. A marked lateral variation in gold/uranium ratios is often a significant feature of a goldfield. The ratio is characteristically zoned parallel to the basin edge and decreases in a basinward direction.

Pyrite is an ubiquitous constituent of auriferous reefs and is commonly extracted for the manufacture of sulphuric acid. Other minor economic constituents of the reef are the platinum group metals and silver.

Gold and uraninite are the most important economic minerals present in the gold reefs while quartz and pyrite are volumetrically the most important and as a result these have been closely studied in recent years. Gold occurs as compact grains often with crystal faces, irregular platy grains or highly irregular porous grains (Saager, 1970). None of these forms are apparently of detrital origin but the close spatial correlation with other heavy minerals strongly suggests that the gold is detrital and has undergone very minor remobilization during metamorphism. Gold in carbon seams occurs either as small grains and patches trapped in columnar carbon, or actually replacing the carbon suggesting that some of the gold was transported in solution as well as in the more common detrital form (Pretorius, 1976). Uraninite is found as tiny angular to well rounded grains commonly rimmed by secondary uraninite. There can be

little doubt that the uraninite is of detrital origin with the overgrowths resulting during metamorphism. Supportive evidence is provided by dating the radiogenic lead which gave ages of about 3400 m.y. while the enclosing sediments, dated from volcanic horizons are in the range 2800 - 2620 m.y. (Minter, 1978). A similar interpretation is placed on the origin of the pyrite although the pyrite grains are larger, more variable in size and display a greater range of morphologies. The detrital origin of the quartz is without question, in spite of the virtually complete obliteration of the original grain morphology by recrystallization, because of the preservation of sedimentary structures such as crossbedding.

# Basin Evolution and Gold Reefs

A variety of hypotheses have been presented in attempts to explain the origin of the Witwatersrand gold deposits, and Pretorius (1975) has compiled a comprehensive summary of these hypotheses. Recent studies of the various goldfields in the Witwatersrand Basin have clearly established that these deposits are fossil placers deposited in a fluvial environment. It is thus clear that these deposits are an intrinsic part of their host lithologies and any attempt to explain their origin without a concurrent consideration for the evolution of the Witwatersrand basin as a whole is patently incorrect.

Structural control is the dominant factor in the evolution and preservation of any sedimentary basin and in the Witwatersrand basin plays a key role in the formation of the auriferous reefs. Initiation of the Witwatersrand basin was accomplished by downwarping of the crust accompanied by volcanic activity and subordinate sedimentation resulting in the formation of the Dominion Reef sequence. This sequence was restricted to the northwestern margin of the incipient basin because of the development of major faulting along this margin. The basin thus developed an asymmetry very early in its existence and maintained its integrity as a typical yoked basin throughout its evolution, with a faulted, tectonically active northwestern margin and a passive, flexured southeastern margin.

The initial subsidence resulted in the formation of a shallow

intracratonic sea. Following the initial volcanism, gentle subsidence took place over the basin with sedimentation in a shallow marine environment depositing the shales and quartzites of the lower Witwatersrand. Minor periodic tectonic activity along the northwestern margin of the repository resulted in the deposition of conglomerates such as the Coronation and Government Reefs. Basin development during this period was characterised by decreasing energy, with basin asymmetry being significant but not well developed. The northwest margin underwent gradual regression while the southeast margin remained essentially static. During lower Witwatersrand times gold and uranium were fed into the basin from an Archean granite/ greenstone belt lying to the northwest of the basin, but in insufficient quantities and under energetically unfavourable conditions to result in the formation of major economic deposits. The presence of this postulated granite/greenstone source area has not been unequivocally established, but small remnants of greenstone belts such as the one near Krugersdorp have been identified. Consideration of the available data and comparison between the Barberton greenstone belt, the greenstone belt remnants to the northwest of the Witwatersrand basin and the Witwatersrand strata led Pretorius (1976a) to conclude that the character of the Witwatersrand sediments is clearly compatible with that of sediments derived from the erosion of a Barberton-type greenstone belt. The minor economic and low grade deposits that were formed essentially constituted a protore which significantly contributed to the primary supply of gold during upper Witwatersrand times. This combination of primary and secondary supply gave rise to the major gold deposits of the upper Witwatersrand.

Upper Witwatersrand deposition was heralded by increased tectonic activity along the basin's northwestern margin. This activity, which continued with increasing vigour throughout upper Witwatersrand times, took the form of episodic uplift of the basin's source area along the marginal faults defining the northwestern margin of the basin. During and between these periods of uplift the basin itself continued its gradual subsidence. Each uplift initiated a period of degradation with active erosion of the source area and the previously deposited Witwatersrand sediments along the basin margin. This initial period of regression caused the deposition of conglomerates in a fluvial environment, probably a braided stream environment

on an alluvial fan surface and debouching into a deltaic environment on the margin of the intracratonic sea. The continuing subsidence of the Witwatersrand basin would cause the regressive regime to cease and transgressive sedimentation would take place until the next episode of uplift. Conglomerates occurring above the base of each major cycle may be explained by one of two processes. Minor periodic movements along the marginal faults could explain these or a geomorphic process described by Schumm (1977, in Minter, 1979b), whereby streams on a fan surface retrench and cut back upslope in an automatic response to slope oversteepening caused by aggradation. In addition thick conglomerate layers are not normally formed by one pulse of sedimentation but rather of the latter mechanism. Inasmuch as each pulse will be deposited on a scour surface, i.e. a local disconformity, these are often sites of gold concentration within the body of a conglomerate horizon.

Periodic marginal uplift had the important consequence of localizing the fans and their conglomeratic horizons along the tectonically active northwestern margin. A total of seven fluvial fan-deltas have been identified along the northwest margin of the Witwatersrand basin (Figure 4). They show a close spatial relationship to the granite domes punctuating the basin. These domes have been interpreted as culminations in Pretorius's (1976b) so-called Vaal-Orange Superimposed Fold Inteference (Vosfi) pattern with the goldfield occupying depressions. This Vosfi pattern is believed to have been initiated prior to Witwatersrand times, continued throughout them and Pretorius suggests that it has remained active into Karroo times. No major fans have been identified along the southeastern margin of the basin, but palaeocurrent data for the Kinross goldfield indicate an entry point from the southeast. Further study is required to resolve this inconsistency. Juxtaposed marginal uplift and gradual basin subsidence resulted in the development of marked unconformities along the basin margin, but these diminish in a basinward direction until they become disconformities (Figure 5). This cyclic tectonism and sedimentation continued with increasing basin instability, as evidenced by the increasing abundance of conglomerates stratigraphically upwards until major tectonism, reflected by the outpouring of the Klipriviersberg lavas, terminated the evolution of the Witwatersrand basin.



Figure 4. Schematic map of the Witwatersrand Basin showing depth of basin, major entry points and fan-deltas. From Minter, 1978.



Figure 5: Section from west eastwards in the O.F.S. goldfields to illustrate upward lifting of strata and overlap of Elsberg beds across the tilted rocks. From Haughton, 1969.

This process/response model linking tectonic activity with the patterns of sedimentation observed in the preserved Witwatersrand rocks explains the lack of stratigraphic correlation between goldfields. The active margin of the basin as a whole will have undergone a similar tectonic history but the movements along the marginal faults were not necessarily simultaneous along the whole margin. In fact studies by Pretorius (1976b) of the East and West Rand goldfields clearly shows an antipathetic relationship between tectonic activity in the two goldfields. Each goldfield probably had a unique tectonic history and its sedimentary record will reflect this. It is important to realise that in spite of gross similarities each goldfield is a unique entity and is not directly related to any other goldfield, nor can valid stratigraphic correlations be made between goldfields.

A model for any ore deposit must explain the three fundamental aspects of source area, transfer system and depository in terms of the observed characteristics of the ore deposit and its environment. Early theories concerning the origin of the Witwatersrand gold deposits were based on a limited variety as well as quantity of data. The two basic theories supported a hydrothermal or a sedimentary origin, but both lacked strong unequivocal supportive evidence. The turning point in this impasse was reached when Steyn (1964, in Minter, 1978) presented the first systematic sedimentological study of a Witwatersrand gold deposit. Since then a number of stuides have clearly demonstrated a close coherence between gold and uranium mineralization and the sedimentary parameters of the host sediments.

In a number of papers, Pretorius (e.g. 1976a) has presented a conceptual model relating sedimentary responses to structural processes which resulted in the deposition of gold and uranium in placer deposits along the margin of the Witwatersrand basin. An important point emphasized in his work is the restriction of placer development to the basin margin, specifically the active margin. The most recent contribution to the literature on the Witwatersrand gold deposits is the synthesis of a large amount of data from the Welkom and Klerksdorp goldfields by Minter (1978). He concludes that the gold deposits were formed in a braided

stream environment on a fan delta. A braided stream environment is supported over a true alluvial fan environment because of the relatively low rate of size decrease of conglomerate pebbles, being of the order of 1 to 1.5 mm. per kilometre (Minter, 1978). Frostick and Reid (1980) in studies on a modern braided stream system obtained figures of about 3 mm. per kilometre and quoted size decreases on modern alluvial fans in excess of 200 mm. per kilometre. They also note that the size decrease is a linear function of distance from source in a braided stream environment as opposed to a strongly exponential function on an alluvial fan. The former is suggested by the data in Minter's (1978) study. Prior to this Pretorius (1976b) presented a strong case supporting, at least in part, a shallow marine deposition for the gold reefs, on the basis of bimodal palaeocurrent directions. He suggested that winnowing by longshore currents played a significant role in the concentration of gold during the formation of the deposits, but Minter rejects this because . he finds no evidence for bimodality and suggests that this may have resulted from the misinterpretation of trough crossbedding and the divergence of channels in a braided stream environment. Minter also confirms the close association between unconformities and disconformities and gold mineralization but extends this by concluding that gold reefs may be formed by transgression or regression over an unconformity or as terminal deposits on disconformities at the top of sedimentary units.

Moving average plots of gold and uranium values by Minter (1976, 1978) define trends in the mineralization on the scale of a goldfied, which closely parallel palaeocurrent directions as measured from sedimentological features of the host sediments. These trends in the basal reef of the Welkom goldfield form an anastomosing pattern characteristic of a braided stream environment. On a smaller scale in the Leader and Elsburg No.5 Reefs, Smith and Minter (1979) studied gold and uranium distributions within individual bars and channels clearly deposited in a braided stream environment, and showed that the mineralization is closely controlled by these features. A similar study by Hirdes (1978) on the Kimberley Reef on the East Rand clearly demonstrated the same close sedimentological control of the gold distribution.

Braided stream environments are characterised by proximal-distal changes in a number of sedimentary parameters such as grain size, mineral ratios and vertical profiles. These parameters have been measured for various reefs (Minter, 1978) and clear proximal-distal relationships have been established. Both conglomerate and detrital mineral (pyrite and zircon) grain size show a steady decrease down the palaeoslope. In a similar way there is a decrease in the percentage of conglomerate present in a vertical profile through the reef. Vertical profiles also show reciprocal increase in carbon content. Mineral ratio changes are best demonstrated by gold/uranium ratios which show a well defined downslope increase. Contoured plots of these parameters and gold and uranium distribution show great similarities, but as yet no attempt appears to have been made to quantify these relationships. This is liable to be difficult if not impossible. Smith and Minter (1979), noting the transient and fluctuating nature of transport in a braided stream environment, developed the so-called point source concept. Periodic reactivation will result in pulses of eroded heavy minerals being fed into the stream which will be locally concentrated at favourable sites in the stream or dispersed in other areas creating a highly variable distribution. These local concentrations will then constitute "point" sources of heavy minerals during subsequent periods of erosion. Processes following this erosion may further concentrate the heavy minerals or disperse them. The important point to note is that if no point sources of heavy minerals exist upstream of a concentration site a local placer cannot be formed irrespective of how optimal the concentration site may be, thus these deposits contain an inherent random factor hindering exact quantification of grade prediction. These local placers are essentially transient features but in an aggrading system these may be buried and preserved. If the heavy minerals have undergone sufficient concentration an economic deposit will result. This can best be represented graphically (Figure 6). This may be extrapolated to a larger scale. In terms of this concept low grade concentrations of gold in the lower Witwatersrand strata can be thought of as point sources of gold for the upper Witwatersrand Reefs. These low grade concentrations are not transient on the same time scale as local concentrations in a stream, but their erosion will liberate gold in much the same way and in some cases may make a significant contribution to the supply of gold derived from erosion of the primary source area.



Figure 6: Schematic model showing effect of local point-sources in determining local placer occurrences. Deposits rich in heavies are most likely where both an efficient concentrating mechanism operated and where the upstream point-source supplied abundant heavy minerals. From Smith and Minter, 1979.

Concentration processes in a braided stream environment are very poorly understood. Smith and Minter (1979) have divided these into four classes in terms of scale. Very small scale processes operate on a millimetre scale and probably include entrapment of particles in voids between larger particles and in fillimentous algae. Small scale processes involve those at the level of bedforms. Pyrite concentrations along foresets of cross beds in quartzites are common and similar gold concentrations have been observed (W.E.L. Minter, pers. comm.). In relation to this an important point which has arisen from recent studies is that the gold particles of the Witwatersrand deposits are not in hydrodynamic equilibrium with the gravels and conglomerates with which they normally occur, but rather with the quartz grains of the overlying sands. Further to this

Minter (1979) has established that the gold was transported as traction load sediments (Figure 7). It is thus probable that the gold concentrations in conglomerates and carbon seams are formed by the physical entrapment of gold carried along at the base of sand bodies passing over unconsolidate gravel bars or algal mats respectively.



Figure 7: C-M diagram (Passega, 1964) demonstrating that the quartz, gold and pyrite grains in Witwatersrand placers were transported as traction load sediments. From Minter, 1979.

Gold concentrations in sandy sediments are more difficult to explain. Uniform transport of hydrodynamically equivalent particles has no intrinsically concentrating effect but gold particles, because of their greater density and smaller size than the sand particles, will tend to settle to the base of any moving sand body. Here any irregularities in the surface over which they are moving may trap the gold particles. A factor to consider is the applicability of the concept of hydrodynamic equilibrium to all natural situations. Hydrodynamic equilibrium is measured under what amounts to laminar flow conditions and it may well be that this equilibrium will change under turbulent flow conditions. If, under turbulent flow conditions the gold grains are in equilibrium with quartz grains having a larger diameter than under laminar flow conditions, then a gold bearing sandbody moving from laminar to turbulent flow conditions will have the sand winnowed out leaving the gold behind. The extent of disequilibrium induced by the transition from laminar to turbulent conditions may be proportional to the degree of turbulence encountered. Areas where such transitions may be expected can be of varying scales but would be characterised by areas of convergent flow and/or abrupt changes in water depth. The studies of Hirdes (1978), Smith and Minter (1979) and Minter (1978) have shown that the foresets of bedforms, channel confluences, channels confined by bank-hugger bars, and the inside arc of a curved reach of a stream, all of which have one or other of the above characteristics, appear to be favourable sites for gold concentration.

Some of these concentration sites fall within the range of Smith and Minter's (1979) medium scale concentrating processes which are operative on the scale of individual segments of a stream system. These may be unique processes such as winnowing on a bar top or may be areas favourable to the operation of one of the smaller scale processes. Large scale processes encompass areas the extent of individual goldfields. These are characterised by regional accumulations of gold caused by an optimal combination of the energy characteristics of the fluvial system and the average grain size of the available heavy minerals.

The Witwatersrand gold deposits are incontrovertable evidence that heavy mineral concentration takes place in a fluvial environment but as yet the exact nature of the concentration processes remains obscure. Very few studies aimed at solving these problems have been carried out, and considerable scope exists for further study. Flume experiments are somewhat limited in their ability to reproduce natural conditions but may provide useful information on the two smaller scale processes. Field studies offer greater potential but an important drawback exists in relation to gold deposits. Gold concentrations are usually very low and thus difficult to study under natural and experimental conditions. The use of higher concentrations of other heavy minerals may yield data which is not applicable to gold because of density and concentration differences. Many problems must be resolved before a clearer understanding of these concentrating processes is arrived at.

### WELKOM GOLDFIELD

### Introduction

The Welkom Goldfield lies 240 km, to the southwest of Johannesburg and comprises a total of 460 square kilometres centred on the town of Welkom in the Orange Free State (Figure 4). Gold exploration commenced in the area in 1933 and just prior to World War II the discovery of the Orange Free State goldfield was announced. During the war years only limited exploration took place but by late 1946 sufficient drilling had been done to warrant the sinking of a shaft on St. Helena Mine. Since that time many more mines have been developed and the town of Welkom came into existence. At present a total of 11 mines (Figure 8) exploit five



Figure 8: Location of mining areas on the O.F.S. goldfield, showing major faults within the Witwatersrand beds and areas of overlaps. From Haughton, 1969.

reef horizons and supply 30% of South Africa's total gold production (Mining Journal, 1980). Production from this field will increase when the Beisa mine comes into production in 1981. Union Corporation is investigating the possibility of opening another mine adjoining Beisa, while Anglo American is planning to form a large mining company to exploit gold deposits in the Erfdeel/Dankbaarheid area of the goldfield. Other mining companies also maintain active exploration programs in the area.

### Stratigraphy

The Welkom goldfield is entirely overlain by Ventersdorp and Karroo rocks and thus the stratigraphy has been elucidated from data derived from boreholes and underground workings. This posed many difficulties, the main ones being the necessity of compiling composite sections from many different boreholes and underground workings, the presence of lateral facies changes and structural complexity in the form of widespread faulting. The stratigraphy is still not well understood and the entire upper Witwatersrand nomenclature is under review at present, but the application of sedimentological studies to the goldfield has gone a long way towards clarifying the complexities.

The presence of Witwatersrand rocks in this area was first established in 1933 when an exploratory borehole intersected sediments tentatively correlated with upper Witwatersrand strata in other areas. Subsequent boreholes confirmed this correlation and intersected payable reef horizons which initiated the establishment of mining operations. These mining operations and the associated exploratory drilling provided an increasing volume of data which allowed the compilation of a stratigraphic column for at least the upper Witwatersrand rocks of the goldfield. The lower Witwatersrand rocks have only a low potential for containing auriferous reefs and are thus seldom drilled and even less frequently exposed in underground workings. Knowledge of the stratigraphy of the lower Witwatersrand rocks in the Welkom goldfield is as a result scanty.

#### Lower Witwatersrand

The lower Witwatersrand in the Welkom goldfield has been subdivided into three groups which are given the same names as in the type area. Similarities in lithology and the presence of certain marker horizons make this correlation valid. Two marker horizons are especially useful. An amygdaloidal lava appears to be the result of an extremely widespread volcanic event and is correlated with the Jeppestown amygdaloid in other parts of the basin. The upper Jeppestown shale unit which terminates the lower Witwatersrand strata has been identified in all the goldfields except the Evander/Kinross field, and probably results from a basin-wide transgressive episode. These two units provide reliable markers for elucidating the lower Witwatersrand strata which can be correlated from goldfield to goldfield.

### Upper Witwatersrand

The upper Witwatersrand in this area has the same basic subdivision as in other goldfields, that is into a lower Main Bird Series and an upper Kimberley-Elsburg Series (Figure 9). The boundary between the two is the upper contact of the upper shale marker which has been correlated with the so-called Kimberley shales in other goldfields. This is one of the very few horizons which can be correlated between goldfields with any confidence.

## The Main Bird Series

The Main Bird Series consists of three fining-upward sedimentary cycles each with an auriferous basal conglomerate. The basal conglomerate of the Main Reef Stage, the so-called Ada May reef, is poorly developed and of little economic significance. This is overlain by some 1175 m. of quartzites with minor gritty horizons and polymictic conglomerates and is terminated by an inferred unconformity. The Intermediate Reefs are developed above this unconformity and form the base of the Livingstone Reef Stage. They consist of a number of oligomictic conglomerate horizons of which the

			010 CT	DOOR THE	Thickness /	CONVENTO	
YSTEN	1 5		SUB - STAGE	ROCK TYPE	METRES	COMMENTS	
KAROO	ECCA ALLANRIDGE BOTHAVILLE RIETGAT / NEW KAMEELDOORNS		sandslone dwyka tillite			MALOR UNCONFOR	міт ч
VENTERSDORP						Allanridge a present eau Fault only preserved wes fault in basins MAJOR UNCONFOR	nd Bothaville st of De Bron t of the De Bron s RMITY
ENTERSDORP						lavas tuffs an structurally r Wilwaters cand	id agglomerates elated to 1 system
UPPER WITWATERSRAND	IES	e. Es	upper elsburg conglomerale		± 274 m	basal conglom	neraiz
	JRG SER	ELS BUR	middle elsburg conglomerale	J.J.Q.Q.Q.Q.Q.Q.Q.Q.Q.Q.Q.Q.Q.Q.Q.Q.Q.Q	±113 m	basal conglon	nerale
	ELSBL		lower elsburg conglomerale	1889 9 7 8 P	±73 m =	basal conglor	nerale
	RLEY	(RLY stales)	"A" REEF zone	800000000000000000000000000000000000000	* 25 m	basal conglur	nerale
	KIMBEI	KIMBE (Gold E	big pebble reef zone	BEBEC	2 ± 10 m	large conglor	nerales lowards base
		н.	<i>"B"REEF zone</i> upper shale marker main bird q zite	2008250	±110 m	basal conglom	nerale
		BIRD RE STAGE	leader reef zone LEADER REEF Teader quartzile khaki shal		± 20m	basal conglom	nerale
	I BIRD SERIE	VINGS TONE EEF STAGE	LASAL REEF upper footwall UF 1 UF 2 UF 3	<u>e o o <del>b</del> b o o b</u> b	± 230m	basai congloi	merale
	MAIN	STAGE RI	UF4 <u>INTERMEDIATE R</u> middle footwall MF 1 MF 2	0.000000000000000000000000000000000000	* 275 m	INFERRED UNCO	NFORMITY
		REFI	MF3 MF4 Iower footwall LF1		±900m		
			LF 2 ADA MAY REEF				

basal horizon is the best developed and most mature. As may be expected this basal horizon is economically the most interesting. Gold values are low and it is as yet unexploited, but uranium values are comparatively high which may make it viable. The relatively high uranium/gold ratio (8-10) observed at President Steyn (Sims, 1969) probably indicates a distal environment, and palaeocurrent data could direct attention to the more proximal areas of greater interest. As with the Main Reef Stage the basal conglomerate zone passes upwards into a sequence of quartzites with minor gritty quartzites and polymictic conglomerates.

The Basal reef is the most important auriferous horizon exploited in the Welkom goldfield. It was originally thought to be the basal unit of the Main Bird Stage but recent work by Minter (1978) indicates that it is a terminal phase of the underlying Livingstone Reef Stage. The Basal Reef will be fully described and discussed in a later section. The Bird Reef Stage is unusual in that it contains two shale units and an auriferous conglomerate horizon within the body of the stage, namely the Leader Reef. The so-called Khaki shale passes upwards into the Leader quartzites which are believed to be unconformably overlain by the Leader Reef. The Leader Reef unit consists of a number of quartzites and auriferous conglomerates which may be divided into two distinct types. The lower member consists of a single to multiple banded oligomictic conglomerate horizon overlain by glassy quartzites, while the upper member is usually a massive polymictic conglomerate which normally rests on the lower member or more rarely on the Leader quartzite. Both members commonly display channeling features which are also found in the overlying quartzite. These often have pebble layers on them which can be highly mineralized. The overlying Main Bird quartzites are superseded by the Upper Shale marker which is the topmost unit of the Bird Reef Stage.

#### Kimberley Elsburg Series

The Kimberley-Elsburg Series is divided into the Kimberley and Elsburg groups. The Kimberley Stage, locally known as the Gold Estates Stage, is composed of three cycles of sedimentation, the 'B' Reef, Big

Pebble Reef and 'A' Reef zones, each separated by an unconformity. All three have basal auriferous conglomerates which pass upwards into quartzites with minor gritty to conglomeratic horizons. The 'B' Reef is a polymictic conglomerate with low gold concentrations in the southern part of the goldfield but becomes oligomictic in the north and carries economic gold concentrations. The Big Pebble Reef is a polymictic to oligomictic conglomerate characterised by cobble-sized pebbles, poor packing and uniformly low gold concentrations. The 'A' Reef is the most variable conglomerate horizon varying from a thin, poorly packed polymictic conglomerate to a thick, well packed highly pyritic oligomictic conglomerate. The economically important oligomictic conglomerates are characteristically restricted to lenticular channel-type deposits with intervening sheet-like polymictic conglomerates with subeconomic gold mineralizations. The oligomictic conglomerates probably represent zones of active reworking in channels with a concomitant enhancement of gold grade. As with the other stages the Kimberley Stage is terminated by an unconformity.

The uppermost stage of the upper Witwatersrand is the Elsburg Stage which, in common with the Kimberley Stage, is composed of three sedimentary cycles separated by unconformities. Each is a fining upward sequence with a basal conglomerate which passes upwards into quartzites. The conglomerates are polymictic and have a very characteristic assemblage of pebbles which differs markedly from other upper Witwatersrand conglomerates. They contain a wide variety of pebbles in a poorly sorted matrix and are characterised by rapid lateral variations in lithology. The conglomerates are poorly mineralized with no economic zones except in a small area to the west of Odendaalsrus. These are the Van den Heevers Rust Reefs which are lensoid bodies of mature oligomictic conglomerates believed to have been derived from the local erosion of earlier reefs.

The Elsburg Stage most clearly shows the effects of the superimposition of two vertical sequences which characterises the upper Witwatersrand. Each sedimentary cycle commenced under high energy conditions following a tectonic movement. The energy level gradually waned as the cycle evolved resulting in a fining upward sequence that was terminated by the next tectonic movement which re-established high energy conditions.

Superimposed upon this sequence is an overall coarsening upward sequence, reflected by the increasing percentage of conglomerate in each of the sedimentary cycles and resulting from the increasing instability of the basin as it evolved. In addition to this vertical change the Elsburg Stage displays a marked lateral zonation, with the percentage conglomerate present decreasing in an easterly direction from the basin margin. Figure 10 shows that the lower Elsburg sub-stage is composed entirely of conglomerate present rapidly decreases to the east and within 7 kms. the conglomerates are only represented by a thin and erratic pebble lag at the base of a thick quartzite unit. This lateral zonation is a characteristic feature of most of the conglomeratic horizons in the upper Witwatersrand.

### Ventersdorp System

The Ventersdorp System is comprised of four stages, a lower and an upper volcanic unit with two sedimentary units between these. The thickness of this system in the Welkom area varies from 0 m. to 1250 m. depending on the level of erosion prior to the deposition of the Karroo strata. The system shows its best preservation, in this goldfield, in large graben structures such as that between the Stuurmanspan and De Bron faults.

The Langgeleven Stage, the correlate of the Klipriviersberg volcanics elsewhere, rests unconformably on the upper Witwatersrand System. It is composed of grey to grey-green andesitic lavas which may or may not be amygdaloidal. This effusive phase was terminated by a period of extensive structural failure giving rise to large horst and graben structures. Rapid erosion and structurally controlled sedimentation gave rise to the sedimentary units of the Ventersdorp System. These are characteristically poorly sorted agglomerates commonly associated with pyritic water-lain tuffs. As may be expected from their inferred depositional environment, the thickness of these sediments is highly variable. The Allanridge Stage is a terminal volcanic phase, very similar in composition



Figure 10; From McKinney, 1964.

to the Langgeleven Stage. It is only preserved in the far northern parts of the goldfield and to the east of the De Bron Fault, having been extensively eroded prior to the deposition of the Karroo System.

The Langgeleven Stage is commonly taken to be the lowermost unit of the Ventersdorp System because of the similarities between it and the Allanridge Stage, but some workers, such as Pretorius (1976b) believe that it is the uppermost unit of the Witwatersrand System. This question is as yet unresolved but is essentially of academic interest. Of considerable economic interest is the occurrence of the Ventersdorp Contact Reef in the Klerksdorp and Carltonville area. In this area the formation of a local marginal yoked basin prior to the effusion of the Langgeleven volcanics resulted in the extensive erosion of upper Witwatersrand sediments, including a number of auriferous horizons. Reworking and deposition of this erosion detritus in a braided stream environment gave rise to the Ventersdorp Contact Reef which was buried by the Langgeleven volcanics very soon after its formation. Unfortunately similar conditions did not prevail in the Welkom area and the Ventersdorp Contact Reef is not developed here.

# Karroo System

The stratigraphic record in the Welkom goldfield has a break of almost 2000 m.y. following the Ventersdorp sequence. Whether the break represents complete non-deposition or whether post-Ventersdorp rocks were deposited and subsequently completely eroded is uncertain but it is clear that the Karroo System was deposited over a surface of considerable relief resulting from a protracted period of terrestrial erosion. The deposition of the Dwyka tillites was strongly controlled by the pre-Karroo topography and its thickness ranges from a few feet to several hundred feet. The tillites contain lava, quartzite and tuff fragments and are interbedded with thick varved shale units, probably representing interglacial episodes. The tillites are overlain by carbonaceous and micaceous sandy shales which grade upwards into cleaner fine-grained quartzites with frequent carbonaceous partings. Two coal seams are present in the upper part of these quartzites and they attain thicknesses in excess of three metres, but their depth and poor quality make them economically unattractive. The quartzites pass upwards abruptly into a monotonous sequence of blue grey shales which continue to surface.

### Structure

The Welkom goldfield is situated on the western flank of a large asymmetric syncline plunging to the north and structurally terminated to the south. This syncline has been broken up into a number of blocks by large faults of various orientations and displacements (Figure 11). The major structural components of the area are two grabens converging to the south on either side of a wedge-shaped horst. The Odendaalsrus graben, to the west of the horst, is bounded by the Border Fault in the west and the De Bron Fault in the east. The Border Fault is believed to be a major fracture with a long and active history and to have had a marked influence on sedimentation during upper Witwatersrand times (Brock and Pretorius, 1964). The De Bron Fault is believed to be a post-Witwatersrand feature. The Odendaalsrus graben has been broken up into longitudinal strips by a number of strike faults such as the Dagbreek and Arrarat Faults. These faults have the fortunate effect of raising the strata in a number of steps across the graben (Figure 12) thus maintaining the gold reefs at accessible levels. Within each of the major stepped blocks, the strata is cut by innumerable lesser order faults which may be strike or oblique faults. Major oblique faults are not a common feature of this graben. Dips in the graben are to the east and average 27° but steepen towards the west and east. The western steepening is a function of tectonic uplift of the basin margin, while the easterly steepening is due to buckling of the strata against the De Bron horst during compression. Anomalous dips in the north and south of the graben give rise to two minor but well defined anticlinal axes.

The so-called De Bron horst is bounded by the De Bron and Homestead Faults. The Homestead Fault converges with and terminates on the De Bron Fault, which gives the horst its wedge shape. The De Bron Fault continues

to the south of the horst and separates the Odendaalsrus and Virginia grabens. There is evidence suggesting considerable dextral movement along the fault in this area (Sims, 1969), as well as substantial vertical movement. The Virginia area is characterised by large transverse faults with only one major strike fault. Deformation by faulting in this area is considerably less complex than in the Odendaalsrus graben. Whereas mining activities in the Odendaalsrus graben are terminated by faulting, the limits to mining in the Virginia area are largely on the basis of assay cutoffs. Dips are gentle in the Virginia area, ranging from 0° to 15°, usually to the west. In the north the strata are generally synclinal while in the south the dips turn northwards reflecting the structural closure of the basin.



Figure 11: Plan of structural features affecting the Witwatersrand succession in the O.F.S. Goldfield. From Haughton, 1969.



Figure 12: Longitudinal section between Western Holdings and Welkom Mines in the O.F.S. goldfield. From Haughton, 1969.
### Basal Reef

The Basal Reef is by far the most important auriferous horizon in the Welkom goldfield. In recent years the rapid increase of the gold price has led to the increased importance of lower grade reefs such as the Leader, 'A' and 'B' Reefs, but none of the other reefs are areally as extensive as the Basal Reef. The Basal Reef is not a single reef as was originally thought, but two laterally coalescing placers deposited on virtually the same palaeo-surface from different entry points. These two placers are called the Basal Reef and the Steyn Reef and between them cover an area of approximately 400 square kilometres, but are generally less than a metre in thickness. In this review the term Basal Reef zone will refer to the entire reef package from the footwall contact to the base of the Khaki Shale irrespective of whether the Steyn or Basal Reef sensu stricto are present. The two placers coalesce along a line which passes eastward through the Western Holdings Mine, then turns northwards near the mine's eastern boundary to pass through the eastern part of the Free State Geduld Mine, until it turns eastward again and crosses the centre of the mine's eastern boundary (Figure 13). Along this line the Steyn placer which lies to the southeast of the boundary laps onto the Basal Reef to the northwest of the boundary, indicating that the Steyn Reef is slightly younger.

Work by Sims (1969) suggests that the Basal Reef may have had a much larger distribution than at present. He equates the lower part of the so-called "double reef" at the President Steyn Mine with the Basal Reef, and suggests that this represents remnants of the originally deposited Basal Reef which has been largely eroded and reworked during the Steyn Reef sedimentation. In spite of observable differences in the character of the two placers and the significant but slight age difference, these placers are considered to have formed under essentially similar conditions. The Welkom Mine exploits the Steyn Reef and as most published data relates to this reef further discussion will be restricted to this horizon, except where specific differences between the two reefs need to be pointed out.



Figure 13: Mining areas in the Welkom Goldfield showing zone of lateral coalescence of the Basal and Steyn Reefs. After Haughton, 1969.

# Stratigraphic Setting

The footwall rocks of the Steyn Reef are coarse grained arenites of the Livingstone Reef Stage. These arenites are khaki to greenish-grey quartzites characterised by abundant yellow speckling caused by the presence of yellow shale fragments in the upper parts of the stage. They are arranged in trough crossbedded cosets separated by thin mud drapes or scour surfaces. Gamma crossbedding occurs interspersed throughout this sequence. Palaeocurrent measurements indicate that the general transport direction for this stage was from the northwest and west-northwest. The Livingstone Reef Stage is interpreted as having been deposited by a braided stream system over a broad distributary front. Rapid progradation into shallow water is thought to have produced an extensive alluvial fan of which this stage would represent the distal part, the more proximal parts having been removed by subsequent erosion. The upper parts of this stage are well known from drilling and underground exposures and within individual mining areas certain persistent units are used as markers to guide development mining. An example of this is the so-called "Allsorts grit" on the President Steyn and Welkom Mines which is a colourful, pyritic small pebble conglomerate that occurs approximately ten metres below the Steyn Reef.

Footwall sedimentation was terminated by tectonic adjustment of the basin margin which resulted in a period of erosion and reworking of the upper footwall sediments. Agradation at the close of this degradational episode resulted in the deposition of the Basal Reef zone sensu stricto. It is important to note that the gold was introduced into the depository and concentrated during the degradation stage and the agrading phase preserved this concentration. A second tectonic adjustment, following closely on the first caused a change in the palaeoslope with accompanying erosion followed by deposition of the Steyn Reef from another entry point. The braided stream system which deposited the Steyn Reef zone largely eroded away the Basal Reef zone where it occurred within its sphere of influence, although remnants were preserved in some areas such as in parts of President Steyn Mine. The margins of the stream system are marked by a zone where the Steyn Reef laps onto the Basal Reef, and to the northwest of this zone the Basal Reef is preserved and no Steyn Reef developed. The Steyn and Basal Reefs will be discussed in greater detail in a later section. The Basal/Steyn Reef sedimentation was terminated by a period of still stand. (Sims, 1969), represented by the sharp planar contact between the Basal Reef unit and the overlying Khaki Shale. Progradation from the south into standing water resulted in deposition of the muds and muddy sands of the Khaki Shale and Leader Quartzite respectively over the whole goldfield. There is evidence in some areas of a break in sedimentation between these two units. On the Free State Saaiplaas Mine pre-Leader Quartzite channels have been found to have been eroded through the Khaki Shale and into the Steyn Reef, and in some cases the Steyn Reef has been removed completely.

Prior to the recognition of this feature serious consideration was given to closing down the mine but when Anglo American Corporation took over the mine their geologists correctly assessed the situation and the mine has operated profitably since then.

The Leader Reef was laid down on an unconformity cutting gently across the older strata. In most parts of the goldfield it lies on the Leader Quartzite but to the east, south and southwest it cuts across the Khaki Shale, Basal Reef zone and rests on footwall rocks. In these areas the Leader Reef transgresses substantially over the sub-outcrop of the Steyn Reef. Sims (1969) states that this has resulted in substantial incorporation of Steyn Reef material into the Leader Reef and the relative enrichment of gold in the latter. Gold was obviously also introduced to these areas, but a different source area to that of the Steyn Reef is indicated by different pebble assemblages and a southwesterly palaeocurrent direction.

### External Geometry

The lower contact of the Basal Reef zone is an erosional surface and the degree of erosion is a function of the hydraulic energy in the area under consideration, as is the thickness of sediment deposited. The palaeosurface on which the Steyn placer was deposited has been exposed over a distance of 20 km down the palaeoslope and is thus an ideal environment in which to examine changes in the sedimentology of the placer, which are related to the downslope decrease in hydraulic energy. In the most proximal areas of the Steyn placer channels up to 4 m. deep have been identified and these appear to branch and join in a braided pattern. These have been filled with mature sediments which ultimately overlapped between the channels to give a sheet of sediment with an irregular channelised base. These channels were incised into a palaeosurface of considerable flatness because it is very seldom that topographic highs project through this relatively thin sheet of sediment. Further down the palaeoslope the hydraulic energy decreased and the effectiveness of channel erosion was diminished. The erosion processes here are represented by gentle small

scallops in the bottom contact of the Basal Reef zone. The agradation which resulted in the deposition of the Basal Reef zone produced an essentially planar surface over which was deposited the Khaki Shale.

The thickness of the Basal Reef zone is related to the hydraulic energy of the system which transported the sediment into the depository. The energy decrease down the palaeoslope is reflected by a sympathetic overall decrease in the thickness of the Basal Reef zone (Figure 14). Superimposed on this general decrease is a variability caused by the irregular nature of the footwall contact. This is especially apparent in the more proximal areas where active erosion has incised channels into the palaeosurface, imposing a braided pattern with a strong north-south trend on the Basal Reef zone isopachs. This is well demonstrated in the area of President Steyn Mine (Figure 14). Further down the palaeoslope channels become less well defined with the width/depth ratios increasing to over 500. This is reflected by thinning of the sediment package and a more uniform thickness. In spite of this a weak braided pattern with a moderate north-south grain can still be detected from the isopachs.

### Lithology

The auriferous reefs of the Witwatersrand in general are characterised by the maturity of their lithology relative to that of their bounding strata. They are normally oligomictic conglomerates with a clean quartz arenite matrix although some of the reefs are, less commonly, polymictic conglomerates. This is the key distinguishing feature between the Basal and Steyn Reefs, which are oligomictic and polymictic respectively.

The Basal Reef, which is more typical of other auriferous reefs present in the Witatersrand sequence, typically has a pebble assemblage comprised dominantly of quartz with less abundant chert and relatively minor quartzite. These proportions are variable depending upon provenance and transport factors but this reef characteristically has less than one or two percent non-durable pebbles which may be quartz porphyry, yellow silicified shale or schist fragments.



The Steyn Reef, in common with some other placers such as the 'B' Reef, has a polymictic pebble assemblage. The pebble assemblage is essentially similar to that of the Basal Reef but it is characterised by a higher percentage of non-durable constituents, especially yellow shale fragments. The proportion of non-durable fragments present can attain as high as 40% as in the southern parts of the President Steyn Mine, but this decreases in a northerly direction down the palaeoslope (Sims, 1969). In the central and northern sections of the Welkom Mine the percentage of non-durable pebbles becomes vanishingly small. This decrease is taken to be an inverse relationship with transport distance. A curious increase in the proportion of smoky quartz pebbles takes place in a northerly direction and this Sims (1969) relates to the degree of radiation damage which is caused by a sympathetic increase in uranium concentration.

# Facies

Minter (1978) has elegantly described the facies present in the Steyn and Basal placers and their vertical and lateral distribution. The main facies identified in Witwatersrand placers are: a scour surface, pebble lag, horizontally layered conglomerate, planar crossbedded pebbly quartzite, trough crossbedded quartzite, planar crossbedded quartzite, horizontally bedded quartzite and thin mud drapes. The proximal areas of the Steyn placer are characterised by a basal scour surface with major channel features, which is overlain by a conglomerate lag which can attain substantial thicknesses in the channel features or as longitudinal bars. The conglomerates grade normally up into trough crossbedded quartzites. Multiple scour surfaces may be present within the quartzite each with a more or less well developed conglomerate lag resting on it. Figure 15 demonstrates this stacking of scour surfaces. In very proximal regions there may be little or no intervening quartzites and the horizon will essentially consist of a thick multiply layered conglomerate. The other above-mentioned facies may or may not be developed within the quartzites. This vertical facies sequence is typical of the south and central parts of the President Brand and President Steyn Mines.



Figure 15. Line drawing of the edge of a Steyn placer channelway in a proximal facies to illustrate multiple scour surfaces within the channel with associated lag gravels and intercalated trough-crossbedded quartz arenite. The relationship between gold and uranium concentration and channel sediments is shown in the lower drawing

From Minter, 1979.

The Steyn placer shows a characteristic variation in the vertical sequence of facies down the palaeoslope. This lateral facies change is manifested by a decrease in the amount of conglomerate present, a reciprocal increase in trough crossbedded quartzites, the appearance of rare units of tabular planar crossbedded quartzites and horizontally laminated quartzites, and prominant mud drapes and mud clasts. The downslope facies change is accompanied by a downslope decrease in pebble size. Sims (1969) found a decrease in size from greater than 500 mm. in the most proximal parts on the President Steyn Mine to about 10 mm. in the distal reaches in the central parts of the Welkom Mine. Minter (1978) synthesised a large amount of pebble-size data from the whole goldfield and presented it graphically in Figure 16.



Figure 16: Palaeoslope dispersal plan showing pebble-size distribution and current directions for the Steyn placer in the Welkom Goldfield. From Minter, 1978.

The distal Steyn placer is characteristically a quartz arenite unit with a thin pebble lag on a scalloped basal scour. Internal scour surfaces with or without minor pebble lags are commonly present as are mud drapes representing quiescent periods between episodes of sand transport. "Flyspeck" carbon is a common constituent in the lower parts of the Steyn Reef zone, and in addition the basal contact is often marked by a seam of carbonaceous material termed "thucolite" which may be as much as 5 cm. thick. This carbon seam usually contains anomalously high concentrations of gold and uranium. Figure 17 is representative of the type of vertical sequence found in the distal parts of the Steyn placer although the sequence seems abnormally thick to be entirely typical. As can be seen from the two vertical sections in Figure 18 from the study area in the southeastern part of the Welkom mine the sequence is more usually less than one metre thick in common with the thickness of this placer on the Free State Saaiplaas Mine. Studies by Minter (1972) revealed a mean thickness of about 75 cms. for this mine. In spite of being substantially thinner than the example in Figure 17 the reef on both mines still retains its multistoried character suggesting that it is the result of a multiphase event rather than a single simple event.



Fig. 17, A, Very distal Steyn placer sediment composed of trough-crossbedded quartz arenite resting on a well defined disconformity. Younger channelling, which has partly removed and reworked the placer, is distinguished by scour surfaces, yellow mud drapes and mud clasts. B, Scour surfaces, and coarser sediment accumulations are associated with higher gold and uranium concentrations. Samples with trace amounts of gold have been left blank. (Mapped by S. Buck.)

From Minter, 1978.

The lateral facies variation as described above is remarkably similar to that observed in modern braided stream environments on alluvial fans. Boothroyd and Ashley (1975) studied the Scott outwash fan in Alaska and identified a downstream variation in lithofacies and sedimentary structures as represented in Figure 19. The vertical sections lettered



Khaki Shale. Fine ripple laminations Very sharp bottom contact.

cms

82

76

11

Coarse-grained quartzite with sago texture

Glassy quartzite. Medium grained with gradational grain size increase towards base. Generally massive but with minor small weakly developed trough crossbeds. Pyrite and yellow shale fragments concentrated on foresets. Ubiquitous yellow speckling. Minor pyrite.

Gritty quartzite with occasional small pebbles. Flyspeck carbon present. Bottom contact is a scoured surface with pyrite stringers.

Coarse-grained glassy quartzite. Massive, nocrossbeds developed.

Gritty massive quartzites. More mature than above, no shale fragments present.

Basal pebble lag with 5 mm. carbon seam on bottom contact. Numerous pyrite stringers. Sharp irregular scoured bottom contact.

Massive medium-grained speckled quartzite

Figure 18: Vertical profile through the Steyn Reef in the study area, Welkom Mine.

A to D in the figure closely resemble the proximal-distal variations observed in the Steyn Reef. Even the distances over which these changes take place are comparable in the ancient and modern examples. Comparison of these two examples with the braided stream profile models, as proposed by Miall (1978) (Figure 20, Table 2 and Table 3) shows that both follow a proximal-distal change from the Scott type, through the Donjek and South Saskatchewan types to the Platte type. In the Steyn placer the Scott type is rarely preserved because of erosional truncation of the more proximal parts of the placer while the Platte type is seldom exposed because of its sporadic low grade mineralization.



Figure 19: Downstream variation in facies and sedimentary structures. Bar and channel sequences do not fine upward, but are capped by a finer overbank facies that becomes more important in a downfan direction. From Boothroyd and Ashley, 1975.



Fig. 2O, Vertical profile models for braided stream deposits. Facies codes to left of each column are given in Table 1. Arrows show small-scale cyclic sequences. Conglomerate clasts are not shown to scale.

From Miall, 1978.

Facles Code	Lithofacies	Sedimentary structures	Interpretation •		
Gms	massive, matrix supported gravel	none	debris flow deposits		
Gm	massive or crudely bedded gravel	horizontal bedding, imbrication	longitudinal bars, lag deposits, sieve deposits		
Gt	gravel, stratified	trough crossbeds	minor channel fills		
Gp	gravel, stratified	planar crossbeds	linguoid bars or del- taic growths from older bar remnants		
St	sand, medium to v. coarse, may be pebbly	solitary (theta) or grouped (pi) trough crossbeds	dunes (lower flow regime)		
Sp	sand, medium to v. coarse, may be pebbly	solitary (alpha) or grouped (omikron) planar crossbeds	linguoid, transverse bars, sand waves (lower flow regime)		
Sr	sand, very	ripple marks of all	ripples (lower flow		
Sh	tine to coarse sand, very fine to very coarse,	types horizontal lamination, parting or streaming	regime) planar bed flow (I. and u. flow regime)		
SI	sand, fine	low angle (<10°) crossbeds	scour fills, crevasse splays, antidunes		
Se	erosional scours with intraclasts	crude crossbedding	scour fills		
Ss	sand, fine to coarse, may be pebbly	broad, shallow scours including eta cross- stratification	scour fills		
Sse, S	he, Spe sand	analogous to Ss, Sh, Sp	eolian deposits		
FI	sand, silt, mud	fine lamination, very small ripples	overbank or waning flood deposits		
Fsc	silt, mud	laminated to massive	backswamp deposits		
Fcf	mud	massive, with freshwater molluscs	backswamp pond deposits		
Fm	mud, silt	massive, desiccation cracks	overbank or drape deposits		
Fr	silt, mud	rootlets	seatearth		
С	coal, carbona- ceous mud	plants, mud films	swamp deposits		
Р	carbonate	pedogenic features	soil		

Table 2; Lithofacies and sedimentary structures of modern and ancient braided stream deposits (modified from Miall, 1977, Table 111). From Miall, 1978.

Name	Environmental setting	Main facles	Minor facies
Trollheim type (G <sub>I</sub> )	proximal rivers (predominantly alluvial fans) subject to debris flows	Gms, Gm	St, Sp, Fl, Fm
Scott type (G <sub>II</sub> )	proximal rivers (including alluvial fans) with stream flows	Gm	Gp, Gt, Sp, St, Sr, Fl, Fm
Donjek type (G <sub>III</sub> )	distal gravelly rivers (cyclic deposits)	Gm, Gt, St	Gp, Sh, Sr, Sp, Fl, Fm
South Saskatchewan type (S <sub>II</sub> )	sandy braided rivers (cyclic deposits)	St	Sp, Se, Sr, Sh, Ss, Sl, Gm, Fl, Fm
Platte type (S <sub>II</sub> )	sandy braided rivers (virtually non cyclic)	St, Sp	Sh, Sr, Ss, Gm, Fl, Fm
Bijou Creek type (S <sub>I</sub> )	Ephemeral or perennial rivers subject to flash floods	Sh, Sl	Sp, Sr

Table 3: The six principal facies assemblages in gravel- and sand dominated braided river deposits. From Miall, 1978.

### Palaeocurrents

Palaeocurrent directions may be determined from a number of parameters measurable in a sedimentary unit. These include crossbedding, pebble size variation, pebble imbrication, pebble roundness and pebble assemblage variation. Sims (1969) in his study of the Welkom goldfield concluded that crossbedding, pebble size variation and pebble assemblage variation were the three most practical and reliable parameters for the determination of the palaeocurrent direction in the Basal Reef zone depositional environment. The other parameters considered but rejected by Sims (1969) are tabulated in Table 4 with the reasons for their rejection. One parameter not considered by Sims (1969) is the orientation of the scallop shaped scours in the footwall contact of the Steyn Reef. These are erosional features and as such will tend to be elongate parallel to the palaeocurrent in much the same way as stream channels will be, albeit on a much smaller scale. In the distal parts of the Steyn Reef where crossbedding is usually not well defined these can be extremely useful palaeocurrent indicators. The bottom contact of the reef is a

Parameter	Reason for Omission
	No obvious imbrication observed,
Pebble Imbrication	Test observations on Basal Reef using apparent dip method (Schlee 1957) were unconvincing (see text).
	As an environmental index of palaeocurrent imbrication is still subject to controversy.
Ripple Markings and	Rarely encountered in the suc- cession and area examined by the author.
Sand waves	Incidence was recorded whenever seen.
	Many of the pebbles in the reefs have been subjected to more than one cycle of sedimentation.
Pebble Roundness	also
	Roundness increases most rapidly in the first few miles of trans- port thereafter showing little or no change. (Pettijohn 1962 p. 1478).
Pebble Packing Density	ls not an index of palaeocurrent.
Size Distribution Data	Time consuming.
Sand Grain Fabric	Time consuming.
Heavy Mineral Dispersal	Beyond scope of project.

# Table 4. Variables considered but discarded.

plane of relative weakness especially where a carbon seam is present, thus three dimensional exposures of these features are often present in irregular stope faces, facilitating the measurement of their long axes.

Of the various parameters used by Sims (1969) only crossbedding measurements give a quantitative estimate of the palaeocurrent direction. Crossbedding measurements in the Steyn Reef on the President Brand, President Steyn and Welkom Mines show a dominant northerly transport direction as opposed to an essentially easterly transport direction for the Basal Reef further to the north. This clearly indicates separate entry points for the sediments comprising the two reefs, thus implying different source areas which is supported by the differing lithologies of the reefs. The Steyn Reef data show great variability and Sims (1969) has interpreted a bimodal distribution. However as Minter (1978) has pointed out the variability is characteristic of a braided stream environment and the bimodality may merely be the result of incorrect measurement of trough crossbedding.

Data compiled by Minter (1978) over a larger area is represented in Figure 16 and this substantiates an overall northerly palaeocurrent direction, and in addition displays a superimposed variability indicative of a braided stream environment. The Free State Saaiplaas Mine lies to the east of the area represented in Figure 15 and work by Sims (1969) and Minter (1972) revealed a palaeocurrent direction from the southwest to the northeast. This suggests a radial distribution of palaeocurrent directions from a point south of the presently known limits of the goldfield. This is in agreement with the concept that the Steyn placer was deposited on an alluvial fan surface in a braided stream environment with a relatively restricted entry front to the south of the goldfield. Minter's (1978) compiled data however are indicative of other, probably less important, entry points to the southwest of the goldfield.

Unfortunately relatively few parts of the study area were accessible and even where accessible, crossbedding was very poorly developed in the Reef zone. However a number of palaeocurrent readings could be

obtained from scours in the basal contact, and during mapping by earlier workers a number of readings had been obtained from the study area or its immediate vicinity. A total of 34 readings were obtained and these gave a vectoral mean of 344° with a consistency ratio of 93.70%. The data had a range of 58° which closely approximates the theoretical maximum range of 52° for a braided stream environment. There was no indication of bimodality in the distribution of the data.

### Detrital Minerals

A wide variety of minerals have been identified in the auriferous reef of the Witwatersrand sequence (Table 5), which may be primary, secondary and even in some cases tertiary. The secondary and tertiary minerals are the results of the metamorphism and remobilisation which has affected the primary detrital minerals. The presence of these minerals and a lack of understanding of their mode of origin was the major weapon in armoury of the hydrothermalists in their dispute with the placerists. Most of the minerals in Table 3 are extremely rare in occurrence and are of little economic importance or genetic significance. The following discussion will be limited to the more abundant and economically important primary detrital minerals.

Pyrite is by far the most abundant mineral found in the auriferous reefs constituting up to 3% of the rock and 90% of all the sulphides present. It is unquestionably detrital in origin but has been widely remobilised and recrystallized during metamorphism giving rise to idiomorphic grains of apparently hydrothermal origin and secondary overgrowths on primary grains. A detrital origin is supported by the presence of relict detrital grains but the most compelling evidence is its mode of occurrence. The pyrite grains are generally concentrated in layers parallel to the sedimentary layering, and in the sandy parts of the reef zone pyrite is found concentrated along the foreset planes of crossbedding. Minter (1978) has compiled a large amount of data concerning the size distribution of pyrite grains in the Basal Reef zone, and he found that the pyrite grains displayed an obvious size decrease down the palaeoslope

(Figure 21) in good agreement with the other downslope changes observed in the Basal Reef zone. There were too few sample sites in this study to define any but the broadest pattern but in a more detailed study on the Vaal placer at Klerksdorp the distribution pattern showed a close agreement with those defined by other sedimentological parameters.

### TABLE 5.

Minerals present in Witwatersrand auriferous horizons

Economic minerals	Sulphides	Oxides	Silicates	Others
Gold	pyrrhotite	quartz	muscovite	calcite
Tellurium	leucopyrite	4	sericite	dolomite
	loellingite	cassiterite	pyrophyllite	
Silver	marcasite		chlorite	zenotime
Stromeyerite		chromite	chloritoid	monazite
Proustite	chalcopyrite		biotite	
Dyscrasite	chalcopyrrhotite	columbite		diamond
	cubanite		kaolinite	graphite
Platinum	chalcocite	corundum		0.000
Platiniridium	neodigenite		epidote	
Osmiridium	covellite	magnetite		
Iridosmine	bornite	hematite '	tourmaline	
Sperrylite	tennantite	goethite		
Braggite			garnet	
Cooperite	galena	rutile		
		leucoxene	zircon	
Uraninite	sphalerite	ilmeno-rutile		
Thucholite		ilmenite	sphene	
Brannerite	molybdenite	anatase	3.000	
Uranothorite	bismuthinite	brookite		
Pyrite				
	arsenopyrite			
	skutterudite			
	cobaltite			
	glaucodot			
	linnaeite			
	safflorite			
	gersdorffite			
	niccolite			
	millerite			
	pentlandite			
	bravoite			
	mackinawite			

From Pretorius, 1976b.



Fig 21, Size distribution of detrital heavy minerals in the Steyn placer. A, Size frequency distribution of pyrite nodules and zircon grains at five locations distributed down 20 kilometres of paleoslope. B, The size relationship between pyrite and zircon is the inverse of that expected and reflects a lack of coarse zircons. This discrepancy decreases downslope. Similar reasoning could account for the changing ratio between uranium and gold contents. C, Contours of the mean size of compact pyrite nodules revoal the palooslope dispersal of the Steyn placer and the more distal nature of the Basal placer.

From Minter, 1978.

Zircon is a common but not abundant constituent of the Basal Reef zone. It occurs as minute rounded grains. In common with pyrite it displays a decrease in grain size down the palaeoslope but this is not nearly as well defined. In conjunction with this decrease there is an improvement in sorting as is the case with the pyrite. No similar study has been conducted on chromite but there is a preferential association between zircon and chromite (Coetzee, 1976) and it can be expected to show a similar downslope decrease. The spatial distribution of leucoxene closely follows that of chromite and zircon, but little can be said concerning its grain size distribution because it is almost certainly an alteration product of ilmenite. Small greenish coloured diamonds have been recovered from mines in the East Rand but as yet none have been identified in any of the reefs of the Welkom Goldfield. The economically important minerals apart from pyrite are the ores of gold, uranium and the platinum group metals. The first two are the major ore metals with the platinoids being recovered as by-products. The platinoids are present in concentrations of approximately 12 parts per thousand million and as a result little is known of their mode of occurrence or distribution, except that the Evander Goldfield has concentrations an order of magnitude greater than the other fields. The main minerals are iridosmine and osmiridium which occur as tiny rounded and irregular grains with an average size of 0.055 mm. Iridium and osmium are present greatly in excess of the other platinum group metals and Cousins (1973) considers this to be indicative of a mature placer deposit which is in agreement with the character of the reefs.

The mode of occurrence and distribution of gold and the uranium minerals have, for obvious reasons, been the most closely studied of all the detrital minerals. The normal range in size of gold grains is from 0.005 mm. to 0.5 mm. but grains in excess of 1 mm. have been found (Halbauer and Joughlin, 1972). Grains liberated by hydrofluoric acid treatment displayed a variety of morphologies only some of which have a detrital character. Schidlowski (1968) on the basis of polished section studies concluded that the gold in the Witwatersrand reefs had undergone large scale reconstitution by mechanical reshaping or by an intermediate solution process followed by reprecipitation. He supports the conclusion arrived at by earlier workers such as Liebenberg (1955) that these processes took place essentially in situ with movement caused by remobilization never being more than a few millimetres.

Hallbauer and Joughlin (1972) used chromatographic prints to determine the small scale distribution of the gold particles in conglomeratic reefs. They demonstrated that the particles occur in five different patterns, none of these distributions being consistent over large areas:

> 1) particles which are dispersed throughout the matrix of the reef in a somewhat even manner, and spaced a few millimetres apart,

2) individual particles isolated from one another by distances up to 100 mm.,

 3) particles concentrated in small, isolated and very rich volumes of a few cubic centimetres of matrix, typically 100 mm. apart,
4) particles congregated in small thin patches at either the hanging-wall or footwall contact of the reef,
5) very rich, isolated clusters occupying a few cubic centimetres and spaced 50 mm. or more apart.

These different distributions and their variability are a function of the inhomogenous nature of the primary depositional environment, and result in great variability in gold concentrations with adjacent samples differing by up to four orders of magnitude.

Polished section studies by Schidlowski on the Basal Reef in the Welkom Goldfield revealed the gold was dominantly concentrated in the bottom two or three millimetres of the reef. He also showed the presence of so-called "false footwall" gold concentrations related to the base of succeeding pulses of sedimentation. These concentrations generally have a far lower grade than the basal concentration. They are preferentially located in the lower parts of the reef with the upper parts being virtually devoid of gold. A detailed sampling study of borehole core carried out by Clarke (1976) on the Basal Reef zone at the Welkom Mine demonstrated that 89% of the total gold in the reef was confined to the bottom 20 cms. containing from 61% to 99% of the total gold. Average gold concentrations in the Basal Reef zone range from 15 ppm. to 60 ppm, but the basal concentrations can attain several hundred ppm. over a few centimeters. Figure 22 shows the typical distribution of gold concentration with a rich basal concentration and a much weaker "false footwall" concentration in a gritty pyritic zone some 16 cms. above the bottom contact. Pyrite is virtually universally associated with gold concentrations and there is often a good correlation between gold and pyrite concentrations, but there are many exceptions. Where a carbon seam is present on the basal contact gold can reach extremely high concentrations and occurs as encrustations on or replacements of algal filaments and specks interstitial to the filaments.

Uraninite is by far the dominant uranium mineral present in the

Gold	$U_3O_8$	Width	ame		finely laminated shale
g/t	Ng/ C	Cins	74.75	149	l cm. quartz vein on contact
					dark grey quartzite, sago texture
0,5	0,02	18			abundant pyrite stringers
-					grey glassy quartzite
			56,75	2-1-7-62	scattered chert grits with pyrite
					grey glassy quartzite
0.5	0.03	12.2	*		heavy pyrite stringer
.,.		,	44.55	3-0-3-6-5	grits with pyrite
					pyrite stringer
1.2.2.		1.			grey glassy quartzite
9,9	0,02	14,0		eezza-	grits and fine pyrite stringers
			30,55	11	grey glassy quartzite with
		11.05		457.77	heavy pyrite stringer and grits
5,7	0,11	11,25	19,3		scattered grits and fine pyrite stringers
1,11	0,02	6,1	13,2		grey glassy quartzite with fine white speckling
7,3	0,12	4,35	8,85		
399,4	3.30	6,2	0.05	2	fragments
3,0	0,14	2,65	0	and	carbon seam, small quartz pebbles and angular chert fragments
				h	speckled quartzite

Figure 22: Vertical section through the Steyn Reef on the Welkom Mine. After Clarke, 1976.

gold reefs. It is present as tiny rounded grains which have an average size of 0.065 mm. but whose variability in size is not as large as that of gold grains.  $U_3O_8$  concentrations in the Basal Reef zone range from 150 ppm. to 500 ppm. On a local scale there is usually a very close correlation between gold and uraninite concentrations. In the study area a total of 1075 samples were analysed for gold and uranium and a linear regression exercise carried out on the data. This yielded a correlation coefficient of 0.90 which is significant at the 99.5% confidence level. This added support for the contention that the uraninite and gold were transported and deposited at the same time and under the same conditions. However it will be pointed out later and it is important to note that this strong sympathy falls off as the size of the area under consideration increases. An analysis of data from the whole of the Steyn placer would probably yield a correlation coefficient of about 0.60 (W.E.L. Minter, pers. comm.).

Contour plans have been used by a number of authors to represent the areal distribution of gold and uranium mineralization. An early study of this nature was that by Bain (1960) in which he contoured the available sampling data from the Welkom Goldfield. He correctly identified a fluvial pattern in the trends defined by the contours but erred in interpreting the depositional environment as having been a meandering river system which flowed from north to south. Sims (1969) conducted a three part study of gold distribution over the President Steyn Mine using contoured stretch values, moving average contours and trend surface analysis. A stretch value plan was prepared by aggregating together groups of similar values in class intervals of 250 inch-pennyweights. The resultant plan was extremely complicated because of the inherent variability of the sampling data, and was subject to intuitive bias in the contouring, but clearly showed a strong north-south trend paralleling the palaeocurrent direction as defined by the previously discussed sedimentological parameters. The moving average contour plan also showed a north-south grain, although less convincingly, but indicated an overall initial increase in gold content in the direction of the palaeocurrent followed by a well defined decrease. A contour plan for the uranium content was not prepared, but averaged values of uranium content plotted along a north south section line show a peak of maximum values to south

of the area of maximum gold content. Trend surface analysis of reef zone thickness, conglomerate thickness, percentage conglomerate and gold content showed a close correlation between the patterns for each and these patterns could be related to broad geological features. Unfortunately the station spacing used in the analysis was too large to define small scale trends, but Sims (1969) concluded that the close correlation between the sedimentological parameters and the gold content clearly indicated a consanguineous origin.

The most comprehensive compilation and presentation of gold and uranium distribution data in the Basal and Steyn Reefs was carried out by Minter (1978) (Figure 23). A total of 360,000 sample sections of the two reefs were averaged in 100 metre square cells, which were then contoured by a simple moving average procedure. The largest scale trend is one which parallels the basin edge probably reflecting a relationship between the hydraulic energy gradient and the size frequency of the mineral supply. It is interesting to note that the gold and uranium plots are very similar except that the zone of highest uranium concentrations lie further into the basin than that of the gold. This is reflected by a steady increase in the uranium/gold ratio from 5 in the proximal parts of the reef to 40 in the most distal areas (See also Figure 20). This displacement of the uranium distribution relative to the gold distribution may be due to the uraninite grain size population being smaller than that which would have been in hydraulic equilibrium with the gold particle size, but it may also in part be a function of the lower tenacity of uraninite relative to gold. Comparison of the gold and uranium distributions with the sedimentological facies of the reef zone and fan geometry shows that the zone of highest gold concentration corresponds to the midfan while maximum uranium concentrations are developed near the fanbase.

Superimposed on this large scale pattern and perpendicular to it is a smaller scale pattern which is defined by tongues and re-entrants in the contours up and down the palaeoslope and marked trends of better mineralization. The close correspondence between these trends and the palaeocurrent vectoral means can clearly be seen in Figure 23 A.



Fig. 2 3. A, Paleocurrent plan of Steyn and Basal placers showing: their entry positions; boundary of lateral coalescence (marked with T symbols); mean pebble-size isopleths of ten largest pebbles; main trends of best mineralization based on detailed moving-average contours; vectoral means; and the location of heavy mineral sample sites (1 to 5). B, The location and distribution pattern of the high gold content facies in the Basal and Steyn placer deposits. Upslope contour re-entrants are associated with channelways. C, The location and distribution pattern of the high uranium content facies in the Basal and Steyn placer deposits. The fit between gold distribution and paleocurrent data indicates hydraulic control. The position of the uranium facies, downslope from the gold facies, may be related to an apparent lack of coarse-grained uranium. D, A mineralogical ratio change down the paleoslope, expressed by the ratio of uranium to gold, is a useful indicator of the paleoslope gradient and the placer facies. The high ratio area marks the beginning of the heavy mineral distal facies.

On the Welkom Mine a linear zone of better grade mineralization is clearly defined in the block of ground between the De Bron and Arrarat faults (Figure 24). Palaeocurrent data in this area are rare but the two vectoral means available are very similar to the trend defined by the contours. There is also a somewhat weakly defined branching and joining pattern reminiscent of a braided stream. It is interesting to note that the width/depth ratios of the channels on the Welkom Mine are probably of the order of 500 (W.E.L. Minter, pers. comm.). The reef zone thickness in this area is a little less than one metre, thus channel widths would be in the vicinity of 500 metres which is the width of the better grade trends.

The study area, which lies in the southeastern part of this block of ground, contained 1075 sample sites but unfortunately it was only partly mined out, thus leaving gaps in the spread of sampling data. The available data was contoured using a straightforward contouring procedure (Figure 25). This plot failed to define any clear cut trends for either the gold or uranium data. There is some suggestion of a north-south trending branching pattern along the eastern and northern edges of the area especially in the gold plot but it is too illdefined to allow any definite conclusions to be made. Attempts were made to obtain moving average plots of the data to see if this clarified the picture but imcompatibility between the data and the programme prevented the production of these plots. Unfortunately insufficient time was available to modify the data or the programme. A possible reason for the lack of development of any marked patterns may be the widths of the channels in this area. The channel widths in this area are probably of the order of 500 metres and it may well be that the area, which is only 360 metres wide, lies completely within a channel and the contours are merely reflecting withinchannel variance of the mineralization.

Small scale studies have shown the distribution of gold to be highly erratic. Hallbauer and Joughlin (1972) carried out detailed sampling exercises on various reefs, both up raises and within stopes during mining operations. Figures 26 and 27 and Table 6 summarise the results of these exercises. Comparison of the results shown in these two figures indicate that different reefs may be characterised by different



T 0 (T) High gold Intermediate gold Low gold 20 40 60 80 100 metres

Figure 25 A: Gold isocon plan for Steyn Reef in the study area, Welkom Mine.



Figure 25 B: Uranium isocon plan for Steyn Reef in the study area, Welkom Mine.

distribution patterns. No geological data are supplied but it may well be that these contrasting patterns are related to differing sedimentological characteristics of the reef. For instance the clearly defined high grade zones in the Basal Reef section are probably related to channel features in a sheet gravel.



Fig. 26. Values, cm-g, of contiguous chip samples from Basal Reef, Orange Free State. Horizontal line indicates arithmetic mean of sample values

From Hallbauer and Joughlin, 1972.



Fig. 27. Values, cm-g. of contiguous chip samples from Kimberley Reef. Evander. Horizontal line indicates arithmetic mean of sample values From Hallbauer and Joughlin, 1972.

A worrying aspect of the Basal Reef distribution is that the majority of the samples fall below the mean value. Assuming that the arithmetic mean is a valid estimation of the average value of gold present, it can be seen that any random sample taken of this reef will in all probability be lower than the mean value. Boreholes take essentially random samples in this context and it is thus clear that a borehole sample will probably undervalue this section of reef. Table 6 summarises stope sampling data from the 'B' Reef at the Lorraine Gold Mine. The samples were taken at 5 metre centres during the course of mining operations. Adjacent samples show a variation of up to 4 orders of magnitude which is extreme to say the least. Again it is unfortunate that no geological data are supplied as the 'B' Reef is known to be strongly channelised (Minter, 1978) which would in part explain some of the variability. This is supported by the presence of a linear high grade zone across the lower part of the table.

	Sample values, cm-g (T = trace, N = not sampled)									
Date	31:3:60	1	22:4:60	25:5:60	27 :7 :60	15:8:60	7:10:60	14:11.60	22:2:61	
	26		260 000	27 700	450	52	N	215	39	
	26		174	430	94 000	57	N	78	61	
	1485		410	74	930	39	N	Т	30	
	850		425	196	400	102	N	430	22	
	208		280	435	52	102	N	48	17	
	340		1 220	430	2 530	35	N	138	26	
	91		574	720	35	т	4 0 3 0	Т	13	
	65		380	970	208	1 000	91	145	83	
	745		52	465	5 500	158	102	530	215	
	260		N	2740	87	275	• 13	39	1780	
	600		N	325	118	102	158	5 700	13	
	78		N	196	4 680	340	140	1 520	13	
	380		3 0 3 0	270	34 400	965	30 000	13	30	
	430		545	940	7 800	8000	3 5 9 0	87	270	
	1405		78	1 1 50	505	3880	2 360	62 000	118	
	370		30	470	174	1780	135	14 000	225	
	270		145	465	275	181	70	т	48	
Average	450		19 150	2 400	9 000	1000	3 610	5 000	170	

Table 6. Progressive sampling in a mine stope working on the 'B' Reef

From Hallbauer and Joughlin, 1972.

### ORE RESERVE ESTIMATION

Ore reserve estimation is essentially the assessment of the amount, quality and distribution of material that may be profitably mined under given conditions. This requires the collection of sufficient sample data which are manipulated and interpreted to provide a tonnage and grade estimate of sufficient reliability to allow a meaningful economic decision to be made. Ore reserve estimates represent a compromise between the costs of the whole evaluation procedure and the required level of reliability of the estimate. The reliability of the estimate is dependent upon the method of manipulation of the raw data and more importantly on the quality of the raw sampling data. Of the two aspects of the estimates arrived at grade is more sensitive, of more immediate importance and more difficult to estimate than tonnage, thus further discussion will concentrate largely on grade estimation techniques as they are applied to the evaluation of the Basal Reef zone in the Welkom Goldfield. Grade estimation can be conveniently divided into two categories, depending on the source of the data. Borehole cores are usually the only source of sampling data when investigating a gold reef in virgin ground. The sparcity of data points in this type of estimation does not permit the use of sophisticated statistical techniques and renders the full appreciation and utilization of geological parameters of paramount importance. Unfortunately little published information is available on this topic, probably because of a general policy of company secrecy. Far better documented are ore reserve estimations based on underground development and stope sampling. This type of ore reserve estimation is highly amenable to the application of sophisticated statistical techniques because of the large volume of data available. This aspect of ore reserve estimation will receive the greater attention because of the larger volume of literature available and not from any belief that it is inherently more important. The high capitalization costs of establishing a new mine place severe demands on a geologist's abilities to be able to produce reliable ore reserve estimations from a relatively scanty data base. A major problem with all ore reserve estimates is the fact that in most cases it is impossible to assess the precise amount of ore that was present because of geological and mining considerations, thus the efficiency of

different ore reserve estimation techniques can only be indirectly assessed.

## Sampling

Accurate, reproducible sampling is the fundamental basis on which the reliability of all ore reserve estimations rests. Ideally all sample data should be free from error but this is seldom if ever the case in practice, however careful planning and sample acquisition will minimise any errors. Sampling has basically three facets, a strategic facet, an executive facet and an analytical facet. No one facet is of greater importance than any other and all can introduce error if sufficient care is not taken.

The strategic facet of sampling involves the optimization of the balance between the costs of sampling and the reliability of the estimate produced as it relates to the factors of sample density, sampling pattern and sample type taken. Sampling strategy can be decided upon by utilizing theoretical considerations, scientifically controlled tests and/ or an empirical approach.

The type of sample taken during diamond drilling is obviously restricted to borehole core. Sample lengths taken must be defined by the geological characteristics being sampled and efforts must be made to ensure that each sample is geologically as homogenous as possible. The high cost of drilling make it imperative that as much information be obtained from the sample as possible in addition to the conventional parameters of width, lithology and gold and uranium content. Sampling errors, with respect to the assessment of the grade of the intersection, must be guarded against. Core loss is the major problem and in the case of the distal parts of the Steyn Reef where a large proportion of the gold can be contained in a soft, easily lost carbon seam this can be of critical importance. The small size of diamond drill core is an inhibiting factor but often a number of deflections are drilled to obtain a larger sample. This also enhances the number of intersections on a property but does not significantly affect the sample density because of the wide spacing of exploration and evaluation boreholes. Sample density is a function of the cost of drilling and the potential value of the reef. The thick cover of younger rocks in the Welkom Goldfield make drilling an extremely expensive operation, thus reducing the number of boreholes which can be used to test a reef of given potential.

The sampling pattern is not usually decided upon prior to the commencement of a drilling program unless it is possible to extrapolate from known areas. The pattern of drilling normally evolves during the program with each decision being made on the basis of the accumulated data from previous boreholes. This is where geological expertise is of primary importance. A clear understanding of the geological characteristics of the reef being drilled and how these relate to the distribution of the mineralization will reduce the number of boreholes required, while greatly enhancing the quality of the data which are derived from the drilling program. For example the uranium/gold ratio will indicate whether a borehole has been drilled in the proximal or distal parts of a fan and comparison with the ratios in adjacent boreholes will indicate the direction in which the higher grade areas may be expected. A multilineal approach utilizing facies interpretation, pebble sizes, pyrite grain sizes, reef zone thicknesses and other sedimentological parameters will obviously enhance the confidence which may be placed on subsequent decisions.

Underground sampling on the gold mines for ore reserve estimation purposes has largely standardized on the use of channel sampling. Channels 100-150 mm. wide and 10-20 mm. deep are cut perpendicularly across the width of the reef, and these approximate to the crosssectional area of a borehole core, thus allowing direct comparison between the two types of sampling. Sample lengths are based on geological parameters but lack of direct geological control must reduce the reliability of these decisions. In addition in the distal parts of the Steyn Reef only the conglomeratic and gritty zones are sampled, not the whole reef zone. The majority of the mineralization is concentrated in the basal few centimeters of the reef zone but significant amounts of gold may be

present at higher levels (Figure 22). These will not be sampled especially if "false footwall" concentrations are not recognised, and these may be very subtle. The relative thinness of the reef in these areas usually results in its complete extraction during mining, thus a significant negative bias can be introduced into the ore reserve estimate. It is to be strongly recommended that the entire reef zone be sampled.

Channel sampling is used almost exclusively for mine ore reserve estimates because of the relative ease with which a large number of uniform reliable samples may be obtained, at comparatively low cost. In recent years an upsurge in the application of statistical techniques to the data derived from sampling has provided increasing evidence that the size of a sample conventionally taken on the gold mines is too small to provide a reliable estimate of the grade of a particular block of ground. The relatively small size of the samples results in an unacceptably large variance when calculating a mean from their analyses. Hallbauer and Joughlin (1972) showed that only by sampling the complete exposed reef could an acceptable estimate be obtained. Taking into consideration that the estimate so obtained would have to be projected ahead of the face to obtain a grade estimate of the block of ground still to be mined, they suggested that samples a few square metres in size should be taken.

The rationale behind this is easily demonstrated by a simple example. If a 1 kg. block of reef is divided into one thousand 1 g. samples and each is analysed for gold, the mean of these will be the same as if the whole block had been analysed or if the block had been crushed, homogenised, and a single 1 g. sample analysed. If one hundred 1 g. samples had been selected from the unhomogenised block, then their mean would less certainly approximate to the true mean of the block. This certainty would decrease still further if less 1 g. samples were taken. The obvious conclusion is that the larger the physical size of a sample the more reliable would be the estimate of the mean of the gold concentration of the block being sampled based on the same number of samples. There is sound mathematical backing for this concept (Rendu, 1978) but
proof of this is outside the scope of this review. The taking of large samples is obviously statistically desirable. This could be accomplished during ledging prior to the commencement of stoping. Two metre square blocks cut at the planned stoping height could be removed during ledging, crushed, homogenised, a representative sample taken and analysed. An alternative would be to treat the entire sample in a test plant to determine its gold content. The logistics and cost of this type of sampling would have to be balanced against the value of the undoubtedly enhanced reliability of the grade estimate. The reliability of grade estimation is becoming increasingly critical as lower and lower grade ores are becoming economically viable.

The physical collection of a sample may introduce significant error. For the sampling data to be comparable the sample collection procedure must be the same for each sample. Standardization of the sampling procedure is aimed at achieving this but there is no guarantee that each of the many samplers employed by a mine adhere strictly to the standard procedure. The reef itself is not homogenous in its physical characteristics, of which hardness is the most important in terms of sampling. Variations in hardness will reduce the homogeneity of the sampling and cause bias in the sampling results especially if the mineralization preferentially occurs in the harder or softer parts of the reef. Gold is largely concentrated along scour surfaces in the reef and these are planes of weakness especially where carbon is present on the surface, and during sampling larger chips will tend to be broken off precisely where the highest concentrations of gold are to be found.

The sampling pattern in a mine is largely controlled by the geometry of the underground workings while the sample density is a function of the cost versus the required reliability of the grade estimate. Sampling in a raise prior to mining is carried out at intervals varying from 1.5 m. to 5 m. depending on the mine and the reef being exploited. On the Welkom Mine the Steyn Reef is sampled at 2 m. intervals along a raise but with the added modification that alternate walls are sampled at 1 m. intervals and pairs of samples are averaged to provide a single value every 2 m. Owing to the geometry of the mine workings the sampling can only be carried

out on two edges of the block to be evaluated. Royle et al. (1972) conducted a theoretical study on the reliability of this type of "edge" sampling. They showed that irrespective of how dense the sampling was, there will always be a certain finite potential error in the grade estimate of the block which is caused by taking the mean of the "edge" sampling to be the true average grade of the block. Figure 28 shows the sampling patterns considered and Table 7 summarises the kriging variances resulting from the different patterns. The smaller the estimation variance the more reliable is the grade estimate. They did however show that this potential error reduces in size as the number of samples taken increases, which is what may be intuitively expected, but note that the accuracy is partly dependent on the pattern used.



Figure 28: Theoretical "edge" sampling patterns. From Royle et al, 1972.

Table 7 Kriging variance  $\frac{1}{C} \sigma_K^2$  as a function of N and  $\epsilon$ 

Sampling	Number of samples, N	Nugget effect, $\epsilon$		
pattern		0	0.15	0.30
Fig.28(i)	2	0.098	0.152	0-195
Fig.28(ii)	4	0.113	0.153	0.187
Fig.2 8(iii)	6	0.055	0.085	0.110
Fig.28(iv)	8	0.047	0.069	0.088
Fig.28(v)	10	0.044	0.061	0.077

From Royle et al, 1972.

Sampling during stoping operations is aimed at providing an estimate of the grade of the ore mined and to refine the estimate of the grade of the remaining unmined ground in the block. Extending their study from "edge" sampling to "internal" sampling Royle et al. (1972) demonstrated that sampling a block on an internal rectangular grid resulted in a significant reduction in the variability of the sampling data when compared with that derived from the same number of edge samples. Comparison of Figures 28 and 29 and Tables 7 and 8 will make this clear. By applying this concept to a real example Rendu (1976) derived a graphical method of determining the optimal spacing for stope sampling of blocks of various dimensions. He included a method of making allowances for directional trends in the mineralization which is a common feature of the Witwatersrand gold reefs.



Fig.29. Theoretical internal sampling pattern.

Table 8. Kriging variance  $\frac{1}{C} \sigma_K^2$  as a function of N and  $\epsilon$  for patterns having all their samples placed internally

Number of samples, N	Nugget effect, ∈		
	0	0.15	0.30
4	0.023	0.051	0.077
4	0.018	0.050	0.078
6	0.014	0.035	0.056
9	0.011	0.026	0.040
	Number of samples, N 4 4 6 9	Number of samples, N         Nugget 0           4         0.023           4         0.018           6         0.014           9         0.011	Number of samples, №         Nugget effect, є           4         0.023         0.051           4         0.018         0.050           6         0.014         0.035           9         0.011         0.026

Sample collection does not only involve the taking of a physical sample of rock but includes the acquisition of measurements of the characteristics of the reef. The most important of these are the thickness of the reef, its dip and its specific gravity. The reef thickness on a gold mine is conventionally measured as its true thickness but this is not essential. Vertical or horizontal thicknesses can equally well be measured, depending on circumstances, as long as appropriate corrections are applied when calculating tonnages. Specific gravity is an extremely important factor in ore reserve calculations and it is believed that insufficient importance is accorded to its accurate determination in South African gold mines. Each mine uses a standard specific gravity which was determined early in the history of the mine or may merely be an historical average derived from other mines in the area. The standard specific gravity is seldom if ever checked subsequently, certainly not by routine sampling. The Welkom Mine uses an S.G. of 2.78 in its ore reserve calculations. This assumption of a uniform specific gravity throughout a mine must be incorrect and the variation of specific gravity can be shown to introduce significant errors into ore reserve estimates, by means of a simple example.

Quartz and pyrite can, with reasonable accuracy, be thought of as being the only two constituents in a typical reef. The average pyrite content of the Basal Reef zone is 3% (Minter, 1978) but commonly ranges from 1%-10% (Stanton, 1971) and in pyritic quartzites, found in the more distal parts, can attain concentrations of 25% (Pretorius, 1976b). The effect of different pyrite concentrations on the S.G. of this hypothetical quartz/pyrite reef are shown in Table 9 as well as the percentage error in an ore reserve estimate caused by the use of a standard S.G. of 2.78. This is calculated using a pyrite S.G. of 5 and a quartz S.G. of 2.66.

	Table 9	
Pyrite concentration	Reef S.G.	error
1%	2.68	+3.7%
3%	2.73	+1.8%
5%	2.78	0.0%
10%	2.89	-3.8%
25%	3.25	-14.5%

It is thus clear that in areas of low pyrite concentrations the tonnage will be slightly overestimated while high concentration will cause a marked underestimation. Only where the pyrite concentration is 5% will the tonnage be correctly estimated. In the present circumstances on the gold mines this is effectively a hidden error, because of the lack of routine S.G. measurements, and cannot be corrected or allowed for. Serious consideration should be given to including routine S.G. determinations in the normal analytical procedure.

The analytical aspect of sampling is not strictly within the scope of this review but certain characteristics of the mineralization can cause errors in the analytical results if they are not recognised and allowance made for them. No sample is assayed in its entirety thus there is a second sampling stage which takes place in the laboratory. Care must be exercised to ensure that this sample is truly representative of the original sample. This requires as near to perfect homogenization of the original sample as is possible and the fine grain size of the mineralization necessitates yery fine grinding to achieve this. The fine grinding needed obviously aggravates the possibility of losses occurring at this stage. After grinding the sample must be thoroughly mixed before the analytical sample is taken. The great range in densities of the mineral phases present from quartz (S.G. = 2,65) to gold (S.G. = 18) makes it extremely difficult to avoid sorting taking place during mixing. The problems of precision, accuracy and bias from various causes during actual analysis fall outside the scope of this review. They are well known and are guarded against in a well-run laboratory as a part of normal procedure. The problems of analytical accuracy are especially acute when, with the current high gold price, the gold mines could in probability viably exploit certain areas with average grades as low as 2.5 g/t. gold.

# Data Manipulation

Raw data is normally far too complex to interpret reliably except in the simplest cases, and must be manipulated into some more amenable form. In most cases the old adage of not being able to see the wood for the trees is eminently applicable to the interpretation of raw sampling data. The ultimate aim of manipulating sampling data is to produce a single figure which quantifies the characteristic being studied over the area under consideration. This area may be a single mining block, a single mine, a group of mines or the entire earth, and the characteristics being studied, in this case, are the grade and tonnage of Witwatersrand-type gold deposits. It is important to remember that any estimate, for example, of grade, is only one of an infinite number of possible grades of differing probabilities which may be calculated. The allocation of a grade to a particular area of reef must then logically be followed by the determination of how reliable the grade estimate is. This can in part be accomplished by statistical means but a lack of interpretation of the estimate in the light of the geological characteristics of the reef can lead to serious errors of judgement. A large volume of literature exists dealing with the manipulation of sampling data, so as to permit the drawing of inferences regarding a population, from samples of that population. This is the field of mathematical statistics and it is not surprising that it should have found application in ore reserve estimation. Classical statistics were first applied to the problem of ore reserve estimation of the Witwatersrand gold reefs in 1919 (Munro, 1966). The refinement of these statistical techniques advanced sporadically in the following years until in the early 60's work, mainly by Matheron and Krige, iniated the evolution of a branch of statistics termed geostatistics which is aimed at a mathematical description and analysis of geological observations.

## Classical Statistics

Any given set of samples will give rise to a distribution of values and statistics are used to describe the properties of this distribution.

A wide variety of theoretical distributions have been described in statistical literature and two of these appear to be most applicable to the observed distribution of geological data. These are the normal and lognormal distributions and they have been widely applied in ore reserve estimation. A number of statistics, such as the mean, variance, standard deviation, skewness and kurtosis may be used to describe the distribution of sample values. Only some of these are of significance in ore reserve estimation and they need to be defined before showing how they are applied.

Mean (p)

The mean is the most important measure of central tendency and is the average value of the distribution. It is calculated by the formula

$$\mu = \sum_{i=1}^{n} x_i / n$$
 (1)

where  $x_i$  comprises n independent measurements. The mean on its own is obviously of little value in describing a distribution. What is needed is some measure of how the values are dispersed about this mean. The most useful measures are the variance and standard deviation which are closely related to each other.

Variance  $(\sigma^2)$  and Standard Deviation  $(\sigma)$ 

The variance quantifies the average variability of a set of values about the mean of that set of values and is calculated by

$$\sigma^{2} = \sum_{i=1}^{n} (x_{i} - \mu)^{2} / n$$
 (2)

The term  $(x_i - \mu)^2$  is used for two reasons. The term  $(x_i - \mu)$  would sum to zero since positive and negative deviations from the mean would cancel out and in subsequent statistical use  $(x_i - \mu)^2$  is more

useful than the modulus of  $(x_i \neg \mu)$  which is the unsigned deviation from the mean. The standard deviation is merely the square root of the variance and one or the other statistic is used as required by the circumstances. The standard deviation is of great value in statistical analysis because:

it reflects the dispersion of values so that the variability of different sets of data may be compared in terms of the standard deviation,
 it permits the precise interpretation of values within a distribution,
 it, like the mean, is a member of a mathematical system which permits its use in more advanced statistical analysis (Nealon, 1977).

The Normal Distribution

This is the most common theoretical probability distribution used in statistics. It is completely defined by its mean and standard deviation:

$$f(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\{(x-\mu)^2/2\sigma^2\}}$$
(3)

This distribution has the form of a symmetrical bell-shaped curve. An important feature of this distribution is that it is possible to calculate the probability with which the value of a sample from a normally distributed population will lie within a specified range. By calculation it can be shown that: 50% of values in a normal distribution lie within 0.674 standard deviations of the mean 95% lie within 1.96 standard deviations of the mean.

This relationship has been tabulated for the complete range of probabilities and as will be shown later is fundamental to the determination of the reliability of a grade estimate.

The Lognormal Distribution

The lognormal distribution has a positively skewed curve with a long drawn-out tail towards the higher values. This distribution is called lognormal because transformation of data in such a distribution into natural logarithms results in a normal distribution. The curve is thus defined by a very similar equation to that of the normal distribution:

$$f(\mathbf{x}) = \frac{1}{\mathbf{x}\sigma_{N}\sqrt{2\pi}} \frac{e^{\left\{\frac{\ln(\mathbf{x})-\mu_{N}}{2\sigma}\right\}}}{e^{\left(\frac{1}{2\sigma}\right)}}$$
(4)

where  $\mu_N \text{and} \ \sigma_N$  are the mean and standard deviation respectively of the log transformed data.

The mean and variance of lognormally distributed data cannot be calculated by using the equations given earlier because these statistics are unduly influenced by the high values in the drawn-out tail of the distribution. They are given by the following equations:

$$\mu = e^{(\mu + \frac{1}{2}\sigma_{N}^{2})}$$
(5)

and

$$\sigma^{2} = \mu^{2} (e^{\sigma_{N}} - 1)$$
 (6)

This is the so-called two parameter lognormal distribution. Krige (1960) showed that data which did not fit this distribution could be made to do so by addition of a constant ( $\alpha$ ) to each value of the data set. This is termed the three parameter lognormal distribution and data which has been transformed in this manner can be manipulated in the same way as lognormal data. Rendu (1978) describes a convenient method of determining a value for  $\alpha$ .

Estimation and its Precision

The above discussion applies to situations where the entire

population constitutes the data set under consideration. This is very seldom the situation in normal circumstances especially not in a mining context. In mine evaluation the population, i.e. the reef, is sampled and the statistics calculated which are then assumed to apply to the population as a whole. This requires some modifications to the above equations and by further manipulation of the data the reliability of the estimate can be determined.

The variance as calculated in equation (2) is the population variance. To obtain an unbiased estimate of the population variance  $(S^2)$  from sampling data the following equation is used:

$$S^{2} = \sum_{i=1}^{n} (x_{i} - \bar{x})/n - 1$$
(7)

The mean  $(\bar{x})$  is the mean of the sampling data and the term (n-1) is used instead of n to make the sample variance equal on the average to the population variance (Koch and Link, 1970).

When dealing with a lognormal distribution the equation for variance remains valid but unless the variance is known *a priori* serious bias can be introduced by using equation (5) to calculate the mean. To overcome this problem Sichel (1966) developed the 't' estimator to be used when the variance was unknown and had to be estimated from the sampling data. The estimator (t) uses the geometric mean ( $e^{\tilde{X}}$ ) which is multiplied by a factor  $\gamma(\sigma_N^2)$  dependent upon  $\sigma_N^2$  and the number of samples. The mathematical theory behind this factor is extremely complex and to simplify calculations the values for the factor have been calculated and tabulated (Sichel, 1966).

The calculation of the reliability of assuming that the mean of the sampling data is the same as that of the population is based on the Central Limit Theorem. This shows that if a number of sets of sampling data are used to estimate the mean of a population, then these estimates will be approximately normally distributed irrespective of how population is distributed. Consideration of this and the probability/ standard deviation relationship characteristic of the normal distribution make it possible to show that, where  $\vec{x} = \text{sampling mean}$ , S = sampling standard deviation and n = number of samples.

are the upper and lower 95% confidence limits of the estimate of the mean of a normally distributed population.

In the case of a lognormally distributed data the calculation of confidence limits becomes somewhat more complicated. If the population variance is known *a priori*, the confidence limits are calculated for the mean of the logarithmic values using the above method and these are transformed to arithmetic values by using equation (5). In conjunction with the development of the 't' estimator Sichel (1966) also produced tables which can be used to determine confidence limits about the estimator.

# Application

The above discussion is applicable to any population of data and the techniques can be readily used to estimate the average grade of a given volume of gold reef, and similarly to estimate the average reef thickness from which the volume is calculated. If specific gravity were routinely measured this could be processed in much the same way. The use of these techniques is still common on South African gold mines.

The initial stage in evaluating an area of reef is to calculate a weighted average for each sampling section. The gold content at each sample site may be expressed either as a grade in grams/tonne or as an accumulation in centimetre grams/tonne. Neither is inherently correct but certain conditions favour the use of one or the other. The grade is a measure of gold content per unit volume while accumulation is a measure of gold content per unit area. The fact that the majority of the gold is concentrated along the base of a typical gold reef and was deposited there by a near-horizontal movement of fluids would suggest that the accumulation would be the best measure to use (Mendelsohn, 1980). Support for this contention is given by Koch and Link (1970) who point out that the accumulation gives an unbiased estimate of the mined grade of ore where the reef is thinner than the minimum stoping width, which is the case with many reefs such as the distal parts of the Basal Reef zone on the Welkom Mine. On these grounds the accumulation will be used to express the gold content of the reef. An additional consideration is that the use of the accumulation rather than the grade effectively reduces the reef to a two dimensional entity thus simplifying the statistical calculations.

The distribution of the raw sampling data must be determined. This is essentially a subjective decision based on the straightness of the plot of the cumulative frequency curve when plotted on probability paper. Gold values on Witwatersrand gold mines are in the majority of cases found to be distributed three-parameter lognormally. Inspection of Figure 30 clearly shows that this is the case for the study area on the Welkom Mine. In this case the use of the arithmetic mean would not necessarily be incorrect but would clearly be inappropriate. Applying the methods described for determining the mean and confidence limits for normal and lognormally distributed data, to the 1075 sample values from the study area gave the following results for gold:

	Table 10		
	Arithmetic	Sichel 't' Estimator	
Upper 95% Confidence Limit	973cmg/t	940cmg/t	
Mean	912cmg/t	911cmg/t	
Lower 95% Confidence Limit	851cmg/t	883cmg/t	

In this case the estimates of the mean are virtually identical, but the Sichel 't' estimate is significantly superior in reliability. The similarity of the means is probably the result of the relatively large number of samples taken in the study area. It has been shown that as more and more samples are taken from a population with a distribution of any arbitrary shape so the distribution of





the sample mean tends more and more towards a normal distribution (Koch and Link, 1970), thus in the instance where a large number of samples were taken the two estimates of the mean are very similar. In a situation where a smaller number of samples are taken from a lognormal population a significant difference between the two estimates will result and the Sichel 't' estimator will be the more accurate.

A major problem associated with estimating the grade of a block of reef using classical statistics is that no account is taken of any spatial structure of the orebody. Classical statistics are based on the assumption that ore values are randomly distributed and are independent of one another, which is obviously untrue in the case of the Witwatersrand gold deposits. Thus the use of the above described techniques will obscure information which is of use to the geologist. Empirical observations indicate that high values tend to be associated with high values and low values with low values suggesting some form of correlation between values. Attempts to quantify this correlation and to apply it to improving grade estimations led to the evolution of the theory of regionalized variables which provides the mathematical basis of geostatistics.

#### Geostatistics

The geostatistical ore reserve estimation method is based on the relatively simple concept that there is a relationship between the value of a sample and the value of the surrounding ore, and that this relationship is a function of the spatial position of the sample with respect to surrounding ore. This implies that the value of a sample will tell one something of the value of another sample taken near it. This concept is entirely compatible with the currently held views on the genesis of the Witwatersrand gold deposits in which it is believed that gold distribution patterns are related to variations in hydraulic energy levels in the depositional environment. The spatial distribution of gold values may thus be likened to a topographic surface. The theory of randomised variables is used to attempt to conceptualize this

surface by means of the various tools of geostatistics. The main tools used are the variogram and the various kriging methods. The mathematical principles underlying these tools are extremely complex and the following discussion is not intended to be anything more than a very brief look at the nature of these tools, their usage and their possible value in the light of the known geological characteristics of the Witwatersrand gold deposits. It is important to realise that geostatistics attempts to interpret natural observations by mathematical means and this conceptualization is valid only so far as it creates a better picture of reality and assists the solving of practical problems.

The Variogram

The variogram numerically describes a number of features of the grade of an ore deposit which are of interest to the geologist such as the continuity of the mineralization, whether the mineralization is more continuous in one direction than another, the range of influence of a sample and the degree of random variation in the mineralization. These factors are all important in ore reserve estimation and the quantified values for these as derived from the variogram are used in the kriging method. The simplest description of a variogram is that it measures the degree of similarity of two samples taken some specified distance apart, and more importantly in a specified direction.

Without going into the mathematics and semantics of the nomenclature, David's (1977) suggestion will be followed and the variogram function  $(\gamma(h))$  is defined as:

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^{n} \{z(x_i) - z(x_i+h)\}^2$$

where n = number of sample pairs

h = separation of sample pairs in a specified direction  $x_i$  and  $x_i$ +h = sample pair  $z(x_i)$  = value of sample  $x_i$ 

This equation shows a marked similarity to that defining variance in classical statistics. The variogram function differs from variance primarily in that it has a spatial component resulting from the specification of distance and direction in its definition. In fact if the data used to calculate the variogram function satisfies the conditions of second order stationarity (Rendu, 1978, p.14) then with increasing distance (h) the variogram function approaches a limiting value termed the sill which is equal to the population variance. In practice the variogram function is calculated for various values of h and plotted against h. As may be intuitively expected the variogram increases with increasing h showing that the similarity of samples decreases as they are taken further apart. Before calculating a variogram the frequency distribution of the sampling data must be identified. If it is lognormal then the data must be transformed into natural logs which are used in the variogram calculation. The variogram may have a variety of shapes and a number of theoretical models have been proposed to fit these observed shapes. As yet no consensus has been achieved as to which of the models best represents data from the Witwatersrand deposits but the spherical and logarithmic variograms have been widely used.

The spherical model is applicable where there is no drift in the values of the mean in the area under consideration and the variogram is not dependent on the spatial position of the sample pairs. It is one of a group of models characterised by the presence of a sill and its main features are shown in Figure 31. Note that the total variance has been divided into a random and a spatial component. The random component is caused by variation in the mineralization at a scale smaller than the size of the samples taken and is termed the nugget variance. The range of influence is that distance beyond which sample values no longer influence each other.

The logarithmic model is applicable in cases where the mean shows a linear drift but variogram stationarity must be maintained. In this case the variance is a function of the size of the area containing the samples and as a result the logarithmic variogram does not have a sill.



Figure 31: Features of the spherical variogram. From Nealon, 1980.

Figure 32 shows a theoretical logarithmic variogram with a nugget variance (N).  $\alpha$  is a constant related to the population variance, and thus the area containing the samples. The spherical model appears to be valid over limited areas of the Witwatersrand gold reefs, which may be expected from a consideration of the gold distribution in a goldfield. Empirical observations show that the mean value of gold content is different in different parts of the goldfield making the logarithmic

model the more valid, but in small areas this variation in the mean may be insignificant, making the spherical model more applicable. Nealon (1980) presented a variogram from a single raise on the Leader Reef at the Free State Saaiplaas Mine (Figure 33) and this clearly fits the spherical model. It also illustrates an important aspect of the calculation of the variogram function. Variograms may be calculated using single samples to give the so-called 'point' variogram which is the top curve in Figure 33. Alternatively the data can be "regularized" (Rendu, 1978) by averaging sample values in blocks of specified size and the semivariogram calculated from these block averages. The effect of this regularization can be seen in the lower curve where the mean of adjacent samples has been used to calculate the variogram. The curve retains its form but has been considerably smoothed and the overall variance of the data has been reduced. Both curves show an area of influence of 14 m.



variogram model.

From Krige, 1978.

The variogram can also be used to determine if the mineralization displays any preferred direction. Variograms are calculated for a number of different directions and compared. The variogram in Figure 33 was calculated from a raise sampling while that in Figure 34 was calculated



From Nealon 1980



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from sampling along a drive perpendicular to the raise. This variogram is composed virtually entirely of nugget effect and fits the . random variogram indicating no correlation between samples. Sedimentological studies showed that the palaeocurrent direction in this area was parallel to the raise direction, thus parallel to the direction of greater correlation in the mineralization. Many studies have suggested that mineralization trends lie parallel to the palaeocurrent direction thus indicating that these variograms are reflecting a real situation.

This is a simple two direction example but Nealon (1980) extended this study to cover an area of 1175 20m x 20m blocks of regularised sampling data for the Leader Reef. Variograms were calculated for eight different directions and plotting on suitable graph paper indicated that the logarithmic model was most applicable to this data. Using the appropriate formula the slopes of the eight variograms were calculated and plotted on an anisotropy diagram (Figure 35). The direction which produced the variogram with the lowest slope (longest range of influence) identified a preferred orientation in the mineralization (arrow between 6 and 7) which was in close agreement with the studies. An important point which arises from this study is the need for interpretation of the results in the light of geological evidence. The anisotropy diagram was calculated using only the part of the variogram data which best fitted the logarithmic model. If all the data had been used a north-south anisotropy would have resulted which is at odds with the geological data, thus creating doubt as to the correctness of the results of the grade estimation from the subsequent kriging stage.

A similar study was carried out on data from the Steyn Reef in the study area on the Welkom Mine. In this case regularised data in 15m x 15m blocks were used. The plot of the average variogram for gold (Figure 36A) shows a highly erratic distribution of data points which under normal circumstances would be rejected for any further geostatistical evaluation. The uranium data provided a more acceptable fit to a straight line but only up to 8 lags after which it became highly erratic (Figure 36B). The reliability of the results of subsequent procedures is dependent upon the goodness of fit of the data to a theoretical model. In this case the fit is obviously poor but for the sake of completeness the gold data was processed further. The assumption was made that the data fitted

# ANISOTROPY DIAGRAM

MINE	FREE	S	TATE	SAAlplaas	
REEF	LEADE	ER	REEL	F	
METAL	GOLD				

The circle is of unit radius



Figure 35 From Nealon, 1980.



Figure 36: Yariograms for gold and uranium using a logarithmic distance scale. Line fitted by least-squares linear regression.

the logarithmic model and linear regression was used to determine the slopes of the variograms for the eight directions. Only the first eleven data points were used to try and minimize the deleterious effect of the highly erratic spread. These slopes were plotted on an anisotropy diagram which yielded a curious bimodal form rather than the expected ellipse (Figure 37). Bearing in mind the poor quality of the data it is heartening to note that the more pronounced direction has a bearing of 337° which is surprisingly close to the measured palaeocurrent direction of 342°. The variogram is of such poor quality that it would be unwise to ascribe any real significance to this agreement. Similarly the meaning of the minor direction perpendicular to the major trend is obscure and it would be futile to attempt to explain what it represents.

The major use of the variograms is to provide estimates of variables such as range of influence, nugget effect, presence and direction of preferred orientation in the mineralization and the variance/ distance characteristics of the mineralization which are utilized in the kriging method of grade estimation. There are however many other problems which can be greatly simplified by the use of variograms. The design of sampling programs is a field where variograms are especially useful. In any area where a variogram can be computed and applied, for instance by extrapolation from a mined out area into an area of similar mineralization, the relative effectiveness of different sampling patterns and densities can be calculated. Even where data is scanty a number of theoretical variograms can be erected and the results derived from these compared in the light of the available information. David (1977) devotes a section to this application and demonstrates that the information derived from a number of deflections from a borehole is of significantly less value than a single new borehole drilled at a correctly chosen spot.

## Kriging

Kriging is a method of obtaining what has been termed the best linear unbiased estimate (BLUE) of the grade of a block of ore. The technique is almost completely mathematical and little would be gained,

# ANISOTROPY DIAGRAM

MINE	WELKOM	MINE		
REEF	DISTAL	STEYN	REEF	META.
METAL	GOLD			

The circle is of unit radius



Note: Grid north is 12° west of true north.

Figure 37

in the context of this dissertation by attempting a concise description of the method. Many authors (Krige, 1978, Rendu, 1978, David, 1977 and Knudsen and Kim, 1978) give detailed descriptions of the mathematical basis of kriging. Kriging essentially uses weighted averages of samples within a block of ground and within a specified area of influence around the block to arrive at an estimate of the grade of the block. Simply stated, kriging is a technique to find a set of weights that minimizes the estimation variance, according to the geometry of the problem and the character of the mineralization. Kriging can take a variety of forms depending on what form the raw data is in, either point values or block averages and whether the mean of the area being evaluated is known or not. Kriging with a known mean can be carried out in areas where the mean calculated for a mined out area can be reliably taken to represent the mean of an adjacent unmined area which is being evaluated. As may be expected this provides a more reliable estimate than in the more common circumstance where the mean is unknown.

The kriging method is based on the concept of correlation between samples with a decrease in correlation with increasing distance. The variogram numerically captures this relationship between correlation and distance and thus provides the data from which kriging calculates the required weights. The range of influence, degree of correlation as related to distance and direction, and the nugget effect are the important variables derived from the variogram which are used in the kriging technique. The validity of the results obtained by the kriging method is thus obviously dependent upon the goodness of fit of the variogram to the particular model thought to be most applicable. However a good variogram fit does not necessarily mean that kriging may be applied. In the case where the nugget effect exceeds 0.5 the random element of the total variance dominates the spatial element and the application of kriging is inappropriate (Royle, 1972).

The nugget effect of the data from the study area is 0.79, and bearing in mind the poor fit of the variogram, it is unlikely that the use of kriging will produce meaningful results. For the sake of completeness the data were kriged using the parameters established from the

variogram. The occurrence of negative kriging variances clearly showed that the poor quality of the variogram fit adversely affected the reliability of the results and little confidence could be placed in any ore reserve estimates derived from them. However in a case, such as the study carried out by Nealon (1980) where the variogram fit is good and the data derived from it can be related to known geological parameters kriging can be applied and the results confidently used to calculate ore reserve estimates.

#### SYNTHESIS

The various components of geostatistical ore reserve estimation have been described and now a summary of a co-ordinated ore reserve estimation procedure as applied to the Witwatersrand gold deposits will be presented.

The reliability of an ore reserve estimate is fundamentally dependent upon the degree to which the models used to calculate the estimate are representative of reality. This can only be assessed if the nature of the orebody and the factors influencing the distribution of the mineralization in the orebody are clearly understood. The Witwatersrand gold deposits are interpreted as being placer deposits and thus a detailed knowledge of their sedimentological characteristics and how these relate to the distribution of mineralization is of paramount importance in assessing the validity of an ore reserve estimate.

Pretorius (1966) has listed over sixty parameters of a normal conglomerate reef which can be studied quantitatively in order to assess potential of the gold mineralization. At that time only three - gold content, uranium content and reef thickness - were used for ore prediction and evaluation, and this is essentially still the case. This is in part because an ore reserve estimate is a numerical statement synthesising these three parameters and partly because the variability of the mineralization in relation to the other parameters does not permit an exact quantification of these relationships.

Recent studies have shown that mineralization can be related, in a qualitative way, to a number of sedimentological parameters, the more important of which are: clast and heavy mineral sizes, palaeocurrent directions, vertical facies sequences, and heavy mineral populations and ratios (Minter, 1978). It will probably never be possible to utilize any of these parameters in the calculation of ore reserve estimates but they are of considerable importance in the assessment of the reliability of such an estimation. Pretorius's (1966) statement that "only five percent of the information which can be extracted from the rock is actually being used to assess the significance of the rock" is an overstatement of the facts as they relate to ore reserve estimation. The parameters available other than gold content, uranium content and reef thickness are only of qualitative importance to ore reserve estimation and for many the relationship between mineralization and the parameter would be too tenuous to be of value. In any particular area many of the parameters may not be present. In addition the cost of measuring some of the parameters will probably far outweigh the value of these observations.

A detailed knowledge of the geology of a particular deposit is not only important in the assessment of the validity of an ore reserve estimate but also to ensure the applicability of the procedure by which the estimate is arrived at. In general ore reserve estimation procedures require that the mineralization is homogenous within certain prescribed limits. The relationship, albeit qualitative, between geological parameters and mineralization make it possible to divide the orebody into geologically homogenous areas with a reasonable assurance that the mineralization will be similarly homogenous.

Sampling data from each of these geologically homogenous areas are collected and frequency distribution plots used to determine whether the data is normally or lognormally distributed. These plots are also used to determine whether the area is truly homogenous or whether there is more than one population present. Lognormally distributed data which is normally the case with Witwatersrand gold deposits require that the data be transformed into natural logarithms before proceeding further. At this stage the data is usually regularised for ease of handling and to

smooth out irregularities in the data. This data may be manipulated by classical statistical techniques to yield one reserve estimates but the basic assumptions of these techniques and their lack of recognition of the spatial characteristics of the mineralization must cast doubt on their applicability. They may very well provide accurate assessments of the grade but it is difficult to assess their validity in terms of the geological characteristics of the orebody. Geostatistical procedures offer a more attractive alternative because they consider the characteristics of the mineralization and utilize them to estimate the ore reserves. The results are thus easier to interpret in terms of a geological framework.

Variograms provide a powerful tool for quantifying the spatial characteristics of the mineralization and this quantification provides the means by which the kriging procedure can be applied. Comparison between the characteristics of the variogram and the geological parameters of the reef are essential to ensure that the correct theoretical model is used to interpret the variogram. The most important requirement is that the direction of anisotropy as defined by the variogram is in close agreement with the observed mineralization trends and palaeocurrent direction. If the variogram does not fit a theoretical model reasonably well or define an anisotropy parallel to the observed mineralization trends there is little point in continuing to the kriging stage as the results produced will in all likelihood not be significantly superior to those obtained from classical statistical techniques. No generalised statement can be made concerning the applicability of geostatistical techniques to the Witwatersrand gold deposits; each case must be judged on its merits. In the case of Nealon's (1980) study of the Leader Reef it is clear that the application of geostatistical techniques is appropriate and should yield results significantly superior to those from classical statistical techniques. The Steyn Reef study showed that geostatistics were inapplicable but whether this was inherently so or merely a result of insufficient data with an inappropriate spatial distribution is uncertain.

The cognisance of spatial distribution inherent in the kriging

method makes it extremely useful in the design of sampling programs. Armed with a variogram for a particular area, the calculation of kriging variances for different sampling patterns enable the selection of the optimum sampling pattern for a given sample density. By varying the sample density it is possible to determine the value of increasing the density in relation to the increase in cost of the sampling.

The statistical and geostatistical techniques reviewed were predominantly related to the estimation of the mean grade of the mineralization but they are also applicable to the estimation of the mean thickness and mean specific gravity of the reef. Subsequent manipulation of these estimates to determine the mineable ore reserves have not been discussed but Krige (1977) describes the techniques in common usage at present. However the reliability of the results produced by these techniques is directly dependent upon the reliability of the estimates of these three parameters. Irrespective of the technique used to derive these estimates their accuracy can only be assessed in the light of how they relate to the observed geological parameters of the orebody. The importance of geological control cannot be overemphasised. A geostatistician may predict that a block of ground will contain a specified ore reserve but it requires a geologist to inform him that 50% of this block is occupied by a dyke.

#### ACKNOWLEDGEMENTS

I would like to record my sincere appreciation of the much valued assistance and suggestions of Professor R. Mason in the initiation and preparation of this dissertation. In addition his enthusiasm has provided constant stimulation throughout the year.

The members of staff of the Rhodes University Geology Department are thanked for many interesting and informative discussions and their unfailing willingness to provide assistance during the course of the year.

Financial assistance in the form of bursaries from the C.S.I.R. and Southern Sphere Mining and Development Company Limited is gratefully acknowledged. Anglo American Corporation and Welkom Gold Mining Company Limited provided valuable material assistance by allowing me free access to the Welkom Mine, its data records and the use of computer facilities. Suggestions and assistance from Dr. W.E.L. Minter, R. McClennan, E. Nealon and the staff of the Welkom Mine Geology department were gratefully received.

Special thanks are due to my wife, Val, for her unstinting encouragement and support during the year and her patience and perseverance in typing this dissertation.

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