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THE GEOLOGY OF THE WELKOM GOLDFIELD WITH SPECIAL REFERENCE TO THE "A","B" AND BEATRIX REEFS

THESIS

Submitted in Partial Fulfilment of the Requirements for the Degree of MASTER OF SCIENCE (EXPLORATION GEOLOGY) at Rhodes University

by

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ABSTRACT

The first Witwatersrand gold deposits in the Orange Free State were discovered under younger cover rocks in the 1930's with the aid of drilling and geophysics. The Welkom gold deposits are found in the sedimentary rock sequences of the Central Rand Group, which represent unconformity bounded genetic packages. The structural configuration of the goldfield is one of a north to south trending synform that is split near it's axis by the De Bron and Homestead faults.

The "B" Reef is a highly variable, erratically mineralised reef that lies on an unconformity at the base of the Spes Bona Formation. The "A" Reef Zone consists of several placers , including the "Reworked BPM", the Witpan, the Uitsig, the Hanging Wall Grits and the Upper "A" Reef. The Beatrix Reef lies at he base of the Eldorado Formation on an unconformity surface overlying the Virginia Formation in the southern part of the Welkom Goldfield.

The origin of gold in the Witwatersrand basin can be classified into the modified placer theory, the syngenetic theory and the epigenetic theory.

From the distribution of basin edge unconformities it can be deduced that the Welkom fan depository was tectonically active on the western, southern and eastern margins during sedimentation. Palaeocurrent studies indicate that sediment was transported predominantly from the south and west. It is thought

that the "B", "A" and Beatrix Reefs were all deposited in a braided stream environment.

A multidisciplinary approach to ore evaluation of Witwatersrand deposits is considered to be the best method, where sedimentology, geostatistics and structural geology are used.

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1. Introduction

1.1 Aims

This dissertation describes the geology, exploration history , genesis and evaluation of the Beatrix, "B" and "A" Reefs in the Welkom Goldfield. The basic aims of the dissertation are:

i) To discuss the exploration that lead to the discovery of these reefs.

ii) To give a brief overview of the geology of the area.

iii) To give an overview of the various models regarding the origin of the gold in the Witwatersrand placers.

iv) To provide a palaeoenvironmental reconstruction of the Orange Free State goldfield, and

v) To discuss the application of sedimentology and geostatistics in the evaluation of these reef horizons.

1.2 Stratigraphic and structural setting

The Witwatersrand Basin is an Archaean, ENE-trending intracratonic basin, older than 2700 Ma (Armstrong *et al.*,1986) occupying an area of about 42000km^2 (Fig.1). The orebodies discussed in this report are stratigraphically located in the Central Rand Group which will be described in detail later. The Central Rand Group in the Welkom Goldfield underlies younger Proterozoic rocks of the Ventersdorp Supergroup and Karoo Sequence.

The lowermost deposits of the Ventersdorp Supergroup in the Welkom Goldfield belong to the Klipriviersberg Group, and consist of amygdaloidal and non-amygdaloidal, andesitic lavas,tuffs, and agglomerates. After deposition of the Klipriviersberg Group, the region was subject to intense tectonic activity, resulting in the formation of a horst-and-graben topography. The Platberg Group represents the succeeding phase of locally derived sedimentation and volcanism, in response to the volcanic activity. The Pniel Sequence which forms the uppermost parts of the Ventersdorp Supergroup is a sedimentary and volcanic sequence that exhibits regional correlation.

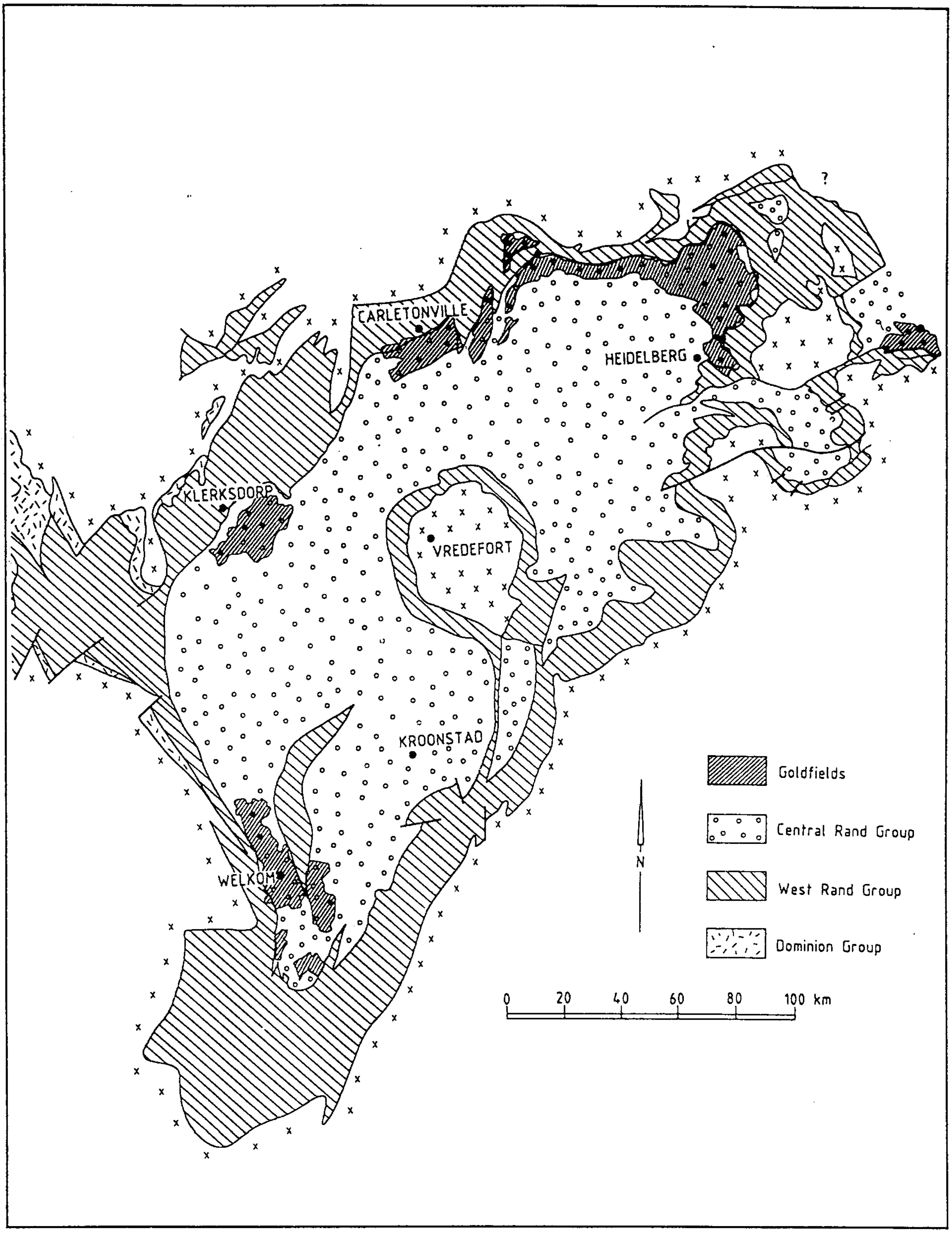

Figure 1 *Sub-Transvaal Sequence outcrop of the Witwatersrand Basin showing the distribution of the Witwatersrand Supergroup and the major goldfields (after Myers et al.,1990).*

The Karroo Sequence covers the entire area. It is thickest over the soft shales of the Pniel Sequence and thinnest over the Klipriviersberg lavas (Winter,1964).

1.3 Study area

The Welkom goldfield as it is known today is shown in figure 2. It covers an area from Allanridge in the north to halfway between Virginia and Theunissen in the south. It includes the towns of Allanridge, Odendaalsrus, Welkom and Virginia. At the moment there are 15 operating mines that up until 1990 have produced 8942 tonnes of gold from 879 million tonnes of ore at an average grade of 10.17g/t (Blamey,1991).

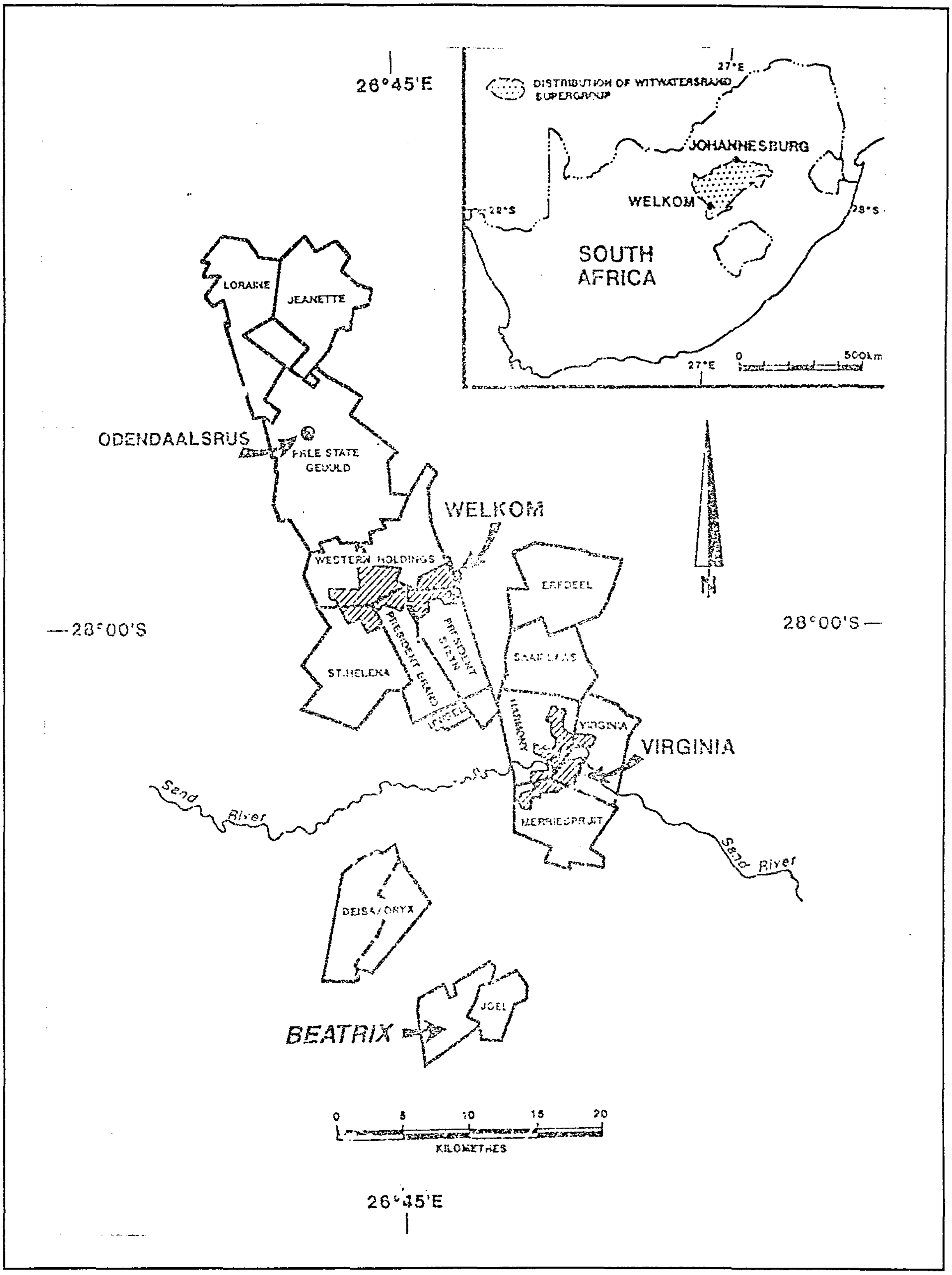

Figure 2 *Plan showing the Welkom Goldfield with the positions of the major towns and gold mines (after Genis,1990).*

2. Exploration history

Before 1900 a conglomerate was noticed on the farm Aandenk, just north of Odendaalsrust, which attracted prospectors (Minter *et al.*,1986). By 1930 shallow shafts and boreholes had been sunk, but without encouraging results. In 1933 a company, called Witwatersrand Extension Limited was formed by Allan Roberts and Emmmanuel Jacobsen. A diamond drill hole (WE1) was drilled down dip from the conglomerate outcrop which intersected Ventersdorp lavas at 184 m. Roberts decided to continue drilling and the borehole intersected Witwatersrand quartzites at 829m. The hole was continued to 1233m but no pay values were encountered. This hole stopped some 120m above the Basal Reef. Several more boreholes were then drilled in the area, two of which passed through the basal reef horizon, but with no pay values.

Dr Krahmann used the magnetometer successfully to map the outer margin of the Witwatersrand Supergroup under younger rocks in the West Wits Line by measuring the location of magnetic shales in the West Rand Group (Roux,1967). The most important magnetic shales are the Water Tower slates, the Contorted bed (a highly magnetite rich banded shale) and the West Rand shales (Roux,1967).

Roux (1967) gives a summary of the densities and thicknesses of the different lithologies that are found in the Witwatersrand basin from which the following figures are taken.

The granite on which the Witwatersrand Supergroup generally rests has a density of 2.63 gm/cc. The rocks comprising the West Rand Group are shales, quartzites and intrusives with densities of 2.63 gm/cc for the quartzites, 2.8 to 3.85 gm/cc for the shales and slates and 2.8 to 3.0 gm/cc for the intrusives. The shales make up about 60 percent, the quartzites 30 to 40 percent and the intrusives 2 to 10 percent of the volume of the West Rand Group rocks. The mean density for the group varies between 2.75 and 2.83 gm/cc, thus making it denser than the granite by 0.12 to

0.20 gm/cc. The total thickness of the formation can be as much as 7000m and is probably nowhere less than 2000m, and thus represents a thick, relatively heavy mass compared with the granite.

The Central Rand Group is comprised predominantly of quartzites with some minor shale bands, conglomerates and intrusive sills. With the quartzites and conglomerates making up 90 percent of the Central Rand Group the mean density is 2.63 to 2.66 gm/cc. The thickness of the Central Rand Group can vary from less than a 1000 metres to 3000 metres. Being thinner and less dense than the West Rand Group it is thus a light mass compared to the West Rand Group.

Lying both conformably and unconformably on the Witwatersrand Supergroup is the Ventersdorp Supergroup, comprised largely of great thicknesses of andesitic lavas with a density of 2.8 to 2.9 gm/cc, and usually lesser thicknesses of sediments, predominantly quartzites and conglomerates. High up in the succession are porphyritic lavas with lower density than the andesitic lavas. The andesitic or basic lavas can be several thousands of metres thick and, contrasting in density by +0.2 to +0.3 gm/cc with the granite and the Witwatersrand quartzites, they form an appreciable heavy mass compared with the lighter rocks. Because of these enormous thicknesses of material and the contrast in densities of around 0.15 to 0.3 gm/cc the Ventersdorp Supergroup produces appreciable gravity anomalies.

Roux (1967) states that the gravity method is useful in two ways. First to establish the existence of a basin of predominantly heavy rocks beneath a cover of younger rocks, usually of Karroo age, and secondly to detail the structure within the basin. Changes of gradient and gravity lows can be indicative of the presence of the lighter Upper Witwatersrand quartzites sandwiched between the heavy West Rand Group and Ventersdorp Supergroup rocks (Figs.3 and 4).

In 1937, a company known as Western Holdings Limited was formed and started exploring areas south of Odendaalsrus, near the Sand River, using the the magnetometer and the torsion balance. The task set was to discover areas where Central Rand quartzites and conglomerates could be expected to occur at shallow depths (Frost *et al.*,1946). O Weiss (Frost, *et al.*,1946) suggested that if the Upper Witwatersrand quartzites occurred anywhere at shallow depth they would, by virtue of their thickness and their lower density (lava 2.85 gm/cc, quartzites 2.65g/cc), cause a detectable gravity low. Shallow drilling targets could be outlined by determining the areas of thinnest lava cover using an Eotvos torsion balance (Minter *et al.*,1986). The heavy West Rand rocks would be indicated by a gravity high with associated magnetic anomalies and the lavas by a gravity high with no magnetic anomalies. By the end of 1937, magnetometer and torsion-balance surveys, under Oscar Weiss's supervision, were almost complete. A very clear gravity anomaly was present around the St Helena farm. These surveys revealed what appeared to be a shallow, elongated dome with a North-South axis over a distance of almost 8km. The centre of this apparent dome was relatively light, with heavier bodies to the East, West and North. The western heavy body was magnetic and the magnetic anomalies indicated a rough North-South strike (Frost *et al.*, 1946).

Figure 3 shows gravity contours over a portion of the area and Figure 4 a gravity and magnetic profile across St Helena Gold Mine. Figure 4 shows the advantage of the aerial magnetic profile over the ground profile. Surface dolerite sills and dykes in the Karroo beds are the cause of the noisy results in the ground profile whereas these effects are largely eliminated from the air. The gravity low occurs to the east of a zone of magnetic anomalies corresponding to anomalies A,B and C in Figure 4. These magnetic anomalies lie on a zone of of high gravity. The interpretation was that the magnetic anomalies and the associated high gravity were due to West Rand Group rocks, that the gravity low was due to Central Rand Group quartzites dipping eastwards, and that the increase of gravity east of the gravity low was

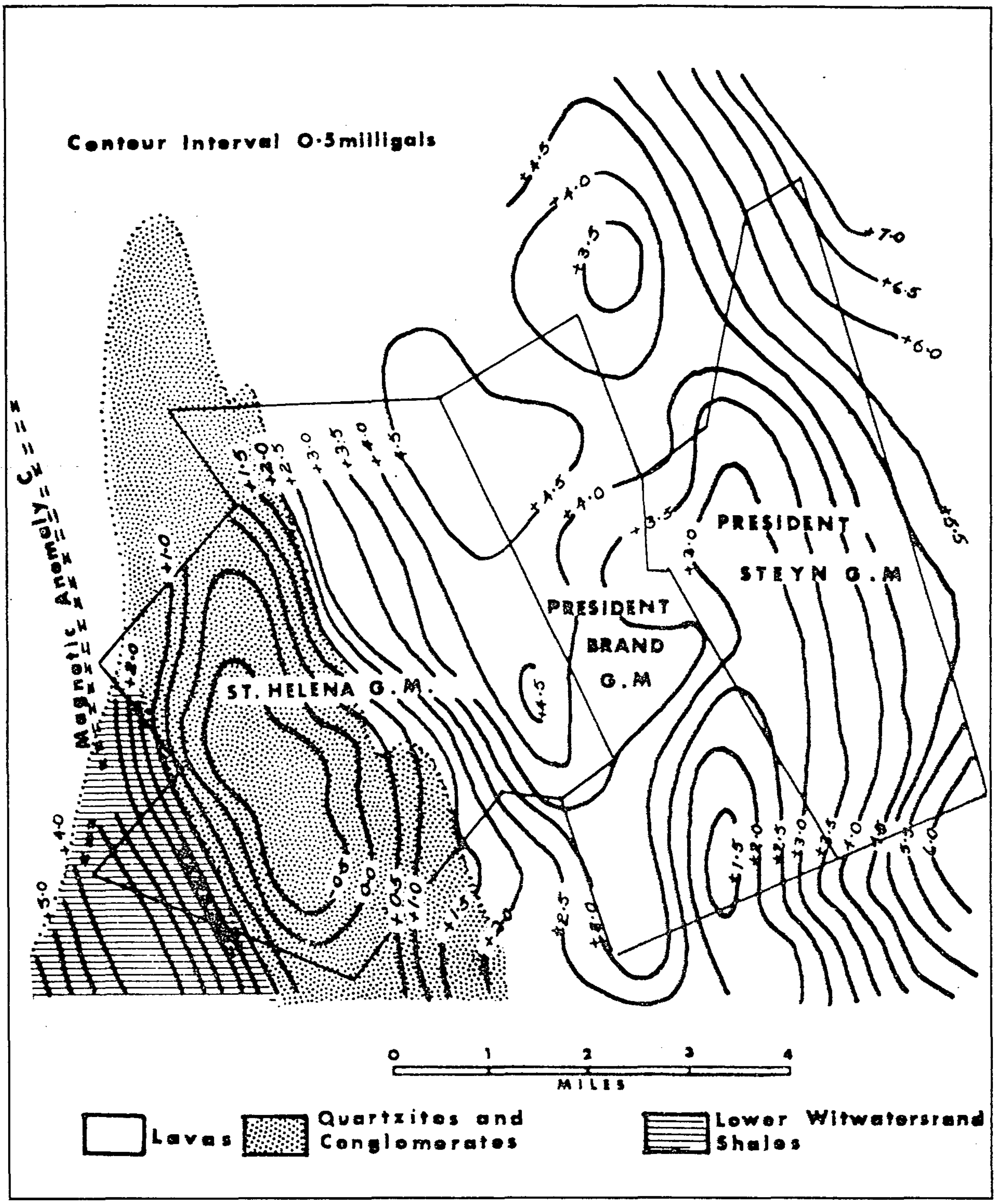

Figure 3 *St. Helena. Gravity contours of portion of the Welkom Goldfield and pre-Karroo geology showing the gravity low which lead to the discovery of the St. Helena Gold Mine (after Roux,1969).*

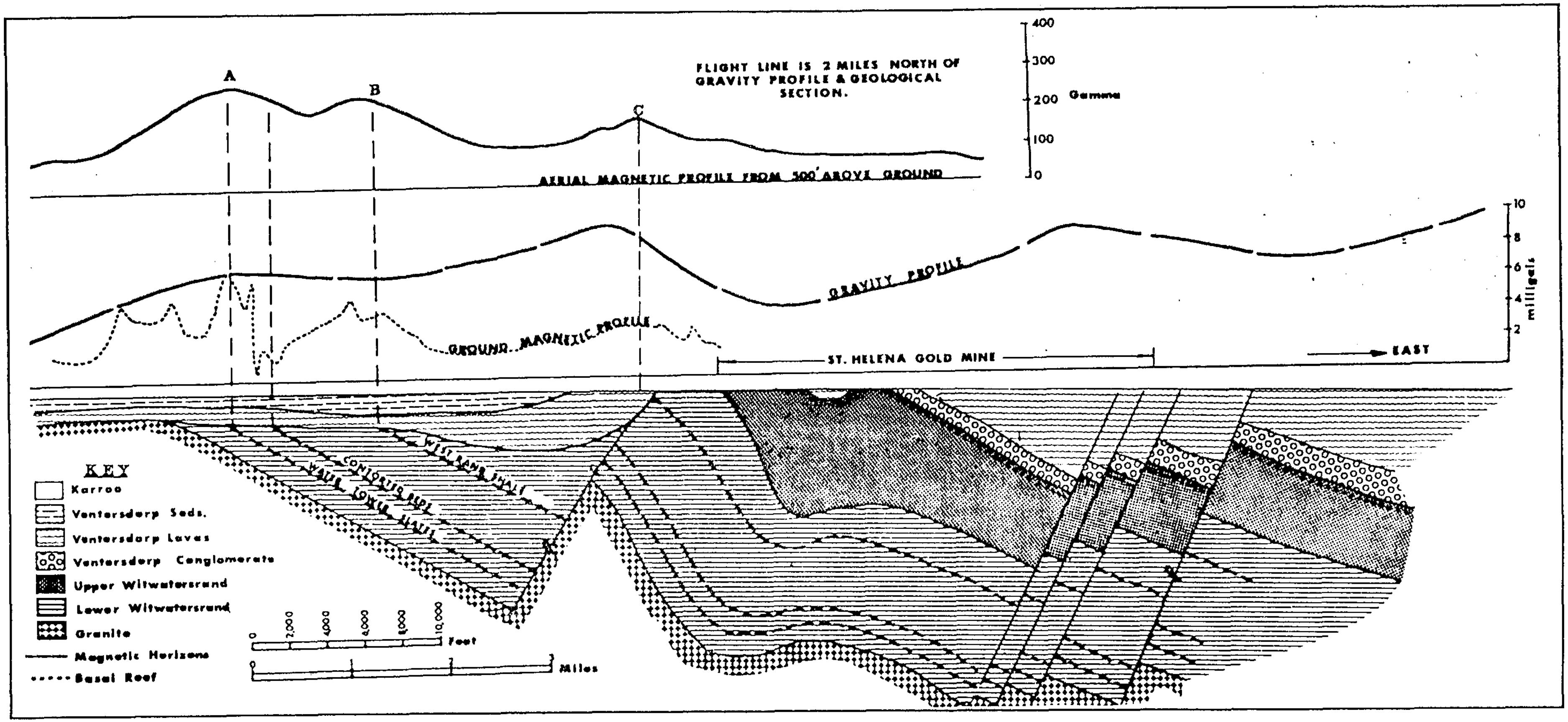

Figure 4 *St Helena. Gravity,ground magnetic and aerial magnetic profiles and geological section across St. Helena Gold Mine and environs (after Roux,1969).*

Payable intersections of structurally duplicated Intermediate reef were intersected at 581m, 737m and 839m in the footwall of the Basal reef.

Subsequent drilling and co-operation between Western Holdings limited and African and European Investment Company Limited led to the intersection and correlation of payable Leader and Basal Reefs between boreholes. When a joint borehole (JBW1) intersected the Basal and Leader reefs an announcement of a major reef strike was made, which lead to further large-scale drilling that proved a wide area of economically significant Basal Reef to the north, south, and east of St Helena. By the end of 1946 there were between 300 and 400 boreholes in the area, and St Helena Gold Mine sank its first shaft in November 1946. This was followed in the next 40 years by the development of a further 16 mines to complete the Welkom Goldfield as it is today.

3.Stratigraphy of the Central Rand Group

The stratigraphy of the Central Rand Group in the Welkom Goldfield consists of a number of sedimentary rock sequences, which Minter *et al*. (1986,p504) describe as unconformity bounded, genetic packages (Fig.5).

3.1. Johannesburg Subgroup

The base of the Johannesburg Subgroup in the Welkom goldfield is transitional with the underlying Jeppestown Subgroup which Minter *et al*. (1986) ascribe to gradual progradation of fluvial fans into shallow - marine conditions. The top of the subgroup is not well defined across the basin because it is comprised of separate fluvial fans, the processes of which were not necessarily co-ordinated, either chronologically or stratigraphically. In spite of this a shale member is used to mark the top of the subgroup. In the Welkom Goldfield this member, known as the Upper Shale Marker (although seldom a shale), is used to mark the top of the subgroup. The Johannesburg Subgroup in the Welkom Goldfield is approximately 1525m thick and is composed predominantly of coarse-grained, argillaceous quartzite (Minter *et al*.,1986). It has been subdivided into five formations which represent genetically-related, individual packages that are

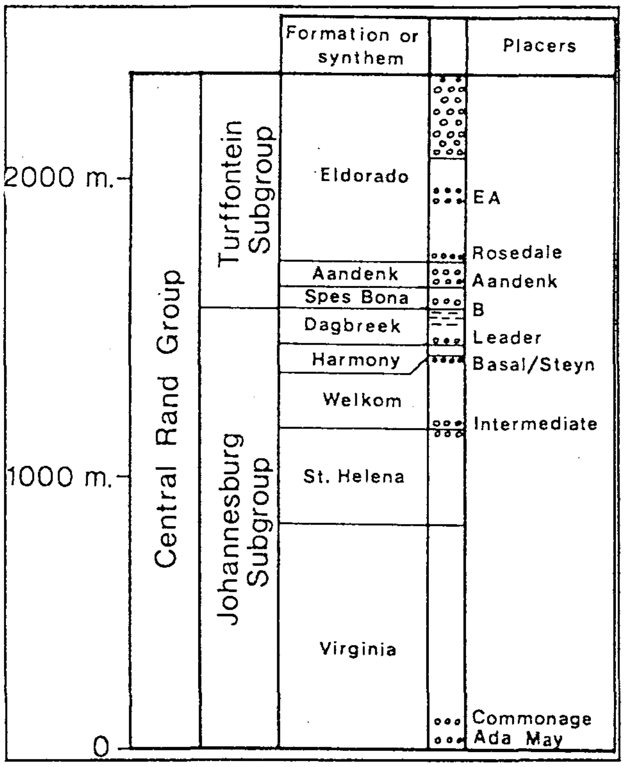

Figure 5 *Stratigraphic column of Central Rand Group in Welkom Goldfield(after Minter et al.,1986)*

separated by unconformities.

The following descriptions of the Johannesburg Subgroup are taken from Minter *et al.* (1986).

Virginia Formation. The formation is up to 800m thick and is composed almost entirely of quartzites which, on the basis of their colour and composition, are divided into between three and six informal units. Collectively, these units are referred to as the Lower Footwall (LF) and have been numbered 1 to 6, from the top downwards. The change from the underlying Jeppestown quartzites to the Virginia formation is transitional. The fine grained, very dark grey to black, highly argillaceeous quartzites coarsen upwards into greenish-grey, coarse-grained, argillaceous quartzite, with scattered layers of small pebbles. The first pebble layer mineralised with uranium and traces of gold is arbitrarily taken as the base of the Virginia Formation. In the Oryx mine area this "pebble layer", known as the Beisa reef, varies from a 5cm-thick quartz-pebble conglomerate to a unit of loosely packed quartz and chert pebbles 150cm thick. A seam, up to 5cm thick on the basal contact, consisting almost entirely of carbon, carries virtually all the gold and uranium mineralization with the latter predominating (Tweedie,1986).

St Helena Formation. This formation is up to 320m thick. Although the strata are predominantly quartzites, persistent beds of supermature quartzite and successions of pebbly layers have been used as markers to subdivide the formation into four informal members. These are known collectively as the Middle Footwall (MF 1-4), and are numbered from the top downwards. The MF1 sediments are pebbly, recording a coarsening upwards of sediment in the fan sequence. Minter *et al.*(1986) interpret this as a sign of fan progradation. These upper, pebbly sediments are overlain by coarser, slightly polymictic, mineralized gravels, up to 2m thick, which represent the base of the Welkom Formation. In an economic sense, these conglomerates are all combined and referred to as the Intermediate Reef Zone or UF4, the best-mineralized placer unit being referred to as the Intermediate Reef. The best -mineralized placers in the Intermediate Reef Zone contain abundant, fine-grained, detrital pyrite, interesting uranium concentrations, and low gold content.

Welkom Formation. This formation thins from 300m on the western side of the goldfield, to 200m on the east. Some of the upper beds thin and disappear in a sedimentary wedge-out, down the eastward palaeodip as indicated by palaeocurrent data. The strata are comprised of argillaceous quartzites and quartzites, with grits and pebbly quartzites in places throughout the sequence. The clast assemblage in the pebbly quartzites is distinctly different from those in the underlying formations, being polymictic and comprising green, yellow, and black lithologies, in addition to vein quartz. The Welkom Formation has been arbitrarily divided into four informal members on the basis of lithology and texture. The formation is topped by the Basal and Steyn reefs, which represent terminal stages in the depositional history of the Welkom Formation fan (Minter *et al.*, 1986).

Harmony Formation. The most typical development of the Harmony Formation occurs on the Harmony Mine, where a maximum thickness of 32m is developed. Three members have been defined on the basis of lithology. They are a basal, Khaki Shale Member, a Waxy Quartzite Member, and a Siliceous Quartzite Member. The *Khaki Shale Member* disconformably overlies the Welkom Formation. The contact is sharp, but it can be observed that muddy sediment percolated about a centimetre into the matrix of the underlying sand. Towards the western and south-western limits of development of the Khaki Shale Member, its characteristic, yellowish, phyllitic appearance becomes that of a laminated, arenaceous shale, with a dark-grey colour. This indicates that in these directions, the unit represents a more proximal position of the depositional basin than where the yellowish shale occurs (Minter *et al.*,1986). The top of the Khaki Shale Member is unconformably overlain by the Waxy Quartzite Member. The remainder of the Harmony Formation consists predominantly of argillaceous quartzites that have a diamictite texture and indistinct bedding. The *Waxy Quartzite Member* averages 18m in thickness, in the Welkom Goldfield. The *Siliceous Quartzite Member* occurs as lenticular, channel-like bodies of light-grey, siliceous quartzite at a number of stratigraphic positions within this waxy quartzite sequence. The lowermost channel bodies contain gold and uranium concentrations reworked from the Steyn placer.

Dagbreek Formation. The Dagbreek Formation is a clastic, wedge-shaped deposit that unconformably overlies the Harmony Formation and is truncated, at the top, by the Spes Bona Formation. The formation is a fining-upward sequence and is subdivided into three members which are known as the Leader Reef Zone, the Dagbreek Quartzite, and the Upper Shale Marker. Because the Spes Bona Formation truncates the Dagbreek Formation, the Upper Shale Marker is absent where isopachs indicated thicknesses of less than 80m for the Dagbreek formation.

3.2.Turffontein Subgroup

Spes Bona Formation. The Spes Bona Formation is approximately 80 metres thick (Minter *et al.*,1986) and generally thins from the nortwest to the south-east in the goldfield. The Big Pebble Marker however, which overlies progressively older Spes Bon sediments to the southeast is transgressed by the Eldorado Formation before the zero isopach of the Spes Bona is reached (Winter,1964). Minter *et al.* (1986) have combined the Spes Bona and Aandenk formations into an isopach analysis (Fig.6). The isopachs close south of the Welkom Goldfield, but on the western flank of the goldfield from Free State Geduld northwards, are cut abruptly by the subcrop of the Aandenk Formation against the Eldorado Formation. This indicates that the Eldorado Formation unconformably overlies the Aandenk Formation and that proximal parts of the Aandenk Formation west of the subcrop, have been eliminated by erosion.It consists of quartzwackes and intercalated polymictic conglomerates overlying a basal conglomerate known as the B Reef. The quartzitic groundmass is usually characterised by a distinctly yellowish or brownish tinge due to the higher sericite content than the grey Eldorado quartzites above (Winter,1957). The quartzites are medium to coarse grained, yellowish grey and impure with many black specks. They are to some degree argillaceous.

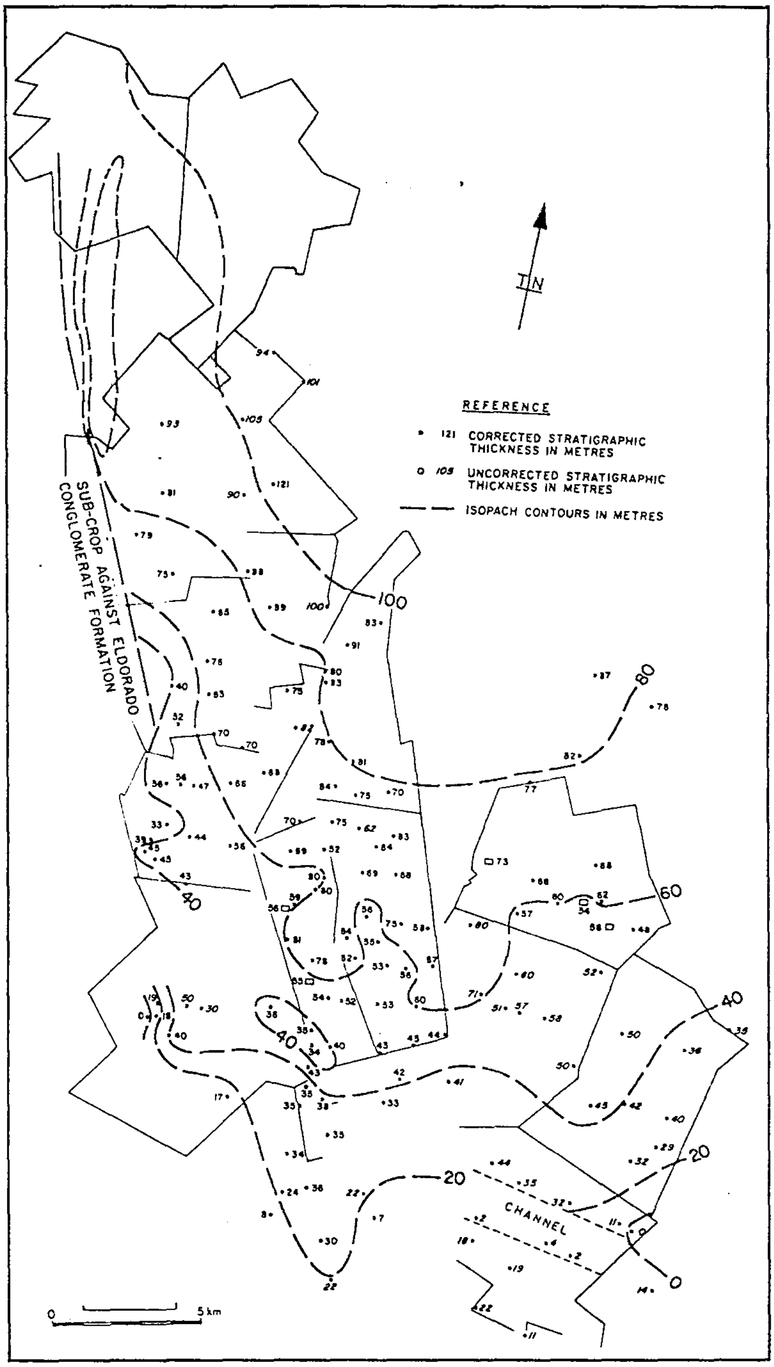

Figure 6 *Isopach plan of the combined Spes Bona and Aandenk formations (after Minter et al,1986).*

The Spes Bona Formation lies unconformably on the sporadically developed Doornkop Formation, or more commonly the Upper Shale Marker (Booysens Shale Formation). The Doornkop quartzite reaches a maximum thickness of 2 metres in the northern parts of Harmony Gold Mine. The Doornkop and Booysens Formations are often eroded by the "B" Reef at Harmony Gold Mine (Swart,1992).

Within the Spes Bona Formation lenticular drapes of shale/silt, up to 15cm thick, define coset boundaries. The polymictic conglomerates are composed of white and smoky quartz, grey, black and layered chert, black shale fragments, and yellow, quartz-porphyry clasts. Within the quartzite individual beds are very lenticular, and trough cross-bedding is conspicuous and coarse grains of black chert and silicified, yellow, lithic fragments are conspicuous. Winter (1957) and Van Biljon (*In* Ellis *et al.*,1991) both describe the Spes Bona Formation as having a general upward fining tendency.

Aandenk Formation. The Aandenk Formation lies unconformably above the Spes Bona Formation. The relief of this palaeosurface is up to 100m. At the base of the Aandenk formation lies the Big Pebble Marker. Winter (1964) suggests that the magnitude of the Big Pebble Marker (BPM) unconformity increases to the west of the De Bron fault. Winter (1957) describes an exposure 400m east of Harmony V2 shaft where the Big Pebble Marker overrides the uppermost conglomerate in zone L.K.1 (the zone which immediately underlies the BPM), enclosing pebbles of this totally different conglomerate in its lower band for some distance east of the line where the transgression of the conglomerate is complete. Coarse material must therefore have moved in the direction of the transgressing shoreline.

Minter *et al.*(1986) equate this unconformity with the base of the Gold Estates Formation in Klerksdorp, the MK1 beneath the Kimberley Reefs in the East Rand, and the MK3 in the Evander Goldfield (Minter *et al.*,1986). They consider this to be a regional surface of contemporaneous erosion, that separates the Johannesburg and Turffontein subgroups better than does the lithostratigraphic Booysens Formation marker.

The sediments are composed largely of very coarse-grained, immature, khaki-coloured quartzites and lesser amounts of black shale/silt, mature quartzite and cobble conglomerates. Several economically important placers occur in the Aandenk Formation.

with a reworking of the BPM. The extent to which these reefs can be correlated is not clear at present (Ellis,in Ellis *et al.*,1991). The 'A' reef package occurs near the middle of the Aandenk Formation. The interval between the 'A' reefs and the base of the Eldorado Formation is typified by alternating successions of quartzwackes, subreywackes and polymictic / oligomictic conglomerates.

Kimberley Channel - Channels and channel fill sequences are common features in the Welkom Goldfield and are regarded as discrete events. These deposits generally comprise polymictic clast and matrix supported conglomerates, diamictites, lithic arenites and quartzwackes topped with mudstone and fine grained sand and/or siltstone. The conglomerates contain medium to coarse pebble clasts and are poorly sorted and massive. The shales and siltstones are frequently horizontally laminated/bedded.

It is apparent that two channel events took place, the first of which was pre-BPM in age whereas the second was post-BPM. An example of this channelling is illustrated by a section through borehole JDR13 (Fig.7). Indications are that the Kimberley Channels eroded into the less competent footwall lithologies and persist along the strike of the footwall which is north-west to south-east (Van Biljon; in Ellis *et al.*,1991). A deep channel of Pre-BPM age has been documented by Winter (1964,p517) on Merriespruit.

The Big Pebble Marker is subdivided into a lower and upper BPM. The lower BPM (termed BPM on Harmony and Anglo American Corporation mines) is a polymictic unit whereas the upper BPM (termed the BPM on Gengold mines and the reworked or rewashed BPM on Harmony Mine) is an oligomictic unit. Where the two units form a composite BPM, as on Harmony Mine, they are separated by an angular unconformity (Swart,1992).

The Big Pebble Marker consists of milky quartz, flint and dark chert pebbles, 2.5-10 cm in diameter, in a light-grey siliceous

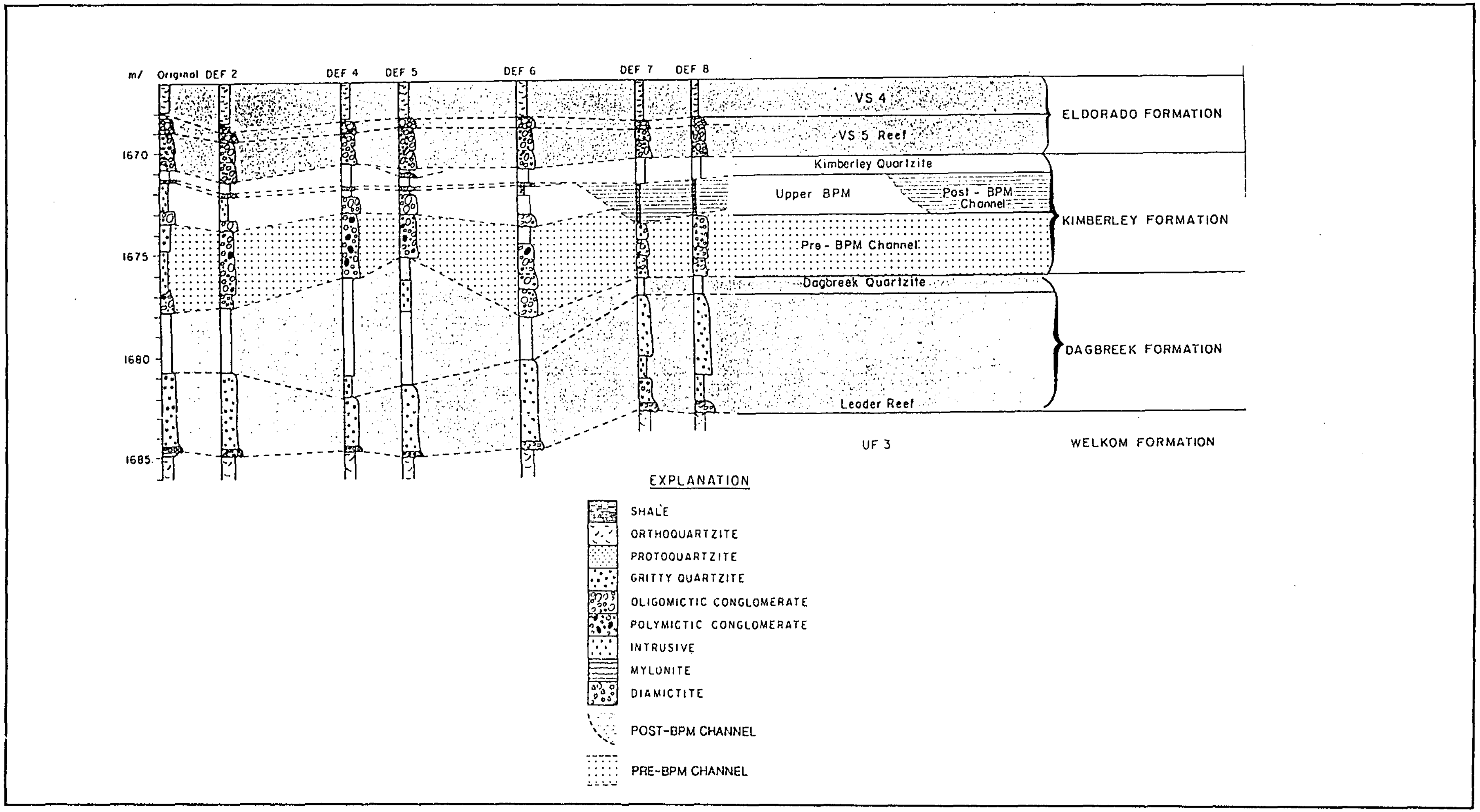

Figure 7 *Section through JDR 13 showing the Pre- and Post-BPM channel (after van Biljon,in Ellis,1991).*

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The Big Pebble Marker consists of milky quartz, flint and dark chert pebbles, 2.5-10 cm in diameter, in a light-grey siliceous quartzite containing coloured fragments. Several bands of quartzite may alternate with the conglomerate, and quartzite may occur between the disconformity at the base and the conglomerate. Gold occurs in rare isolated patches containing pyrite (Winter, 1964). The BPM thickens towards the north where it reaches a maximum thickness of 15 metres at Freddies Cons Gold Mine (Fig.8).

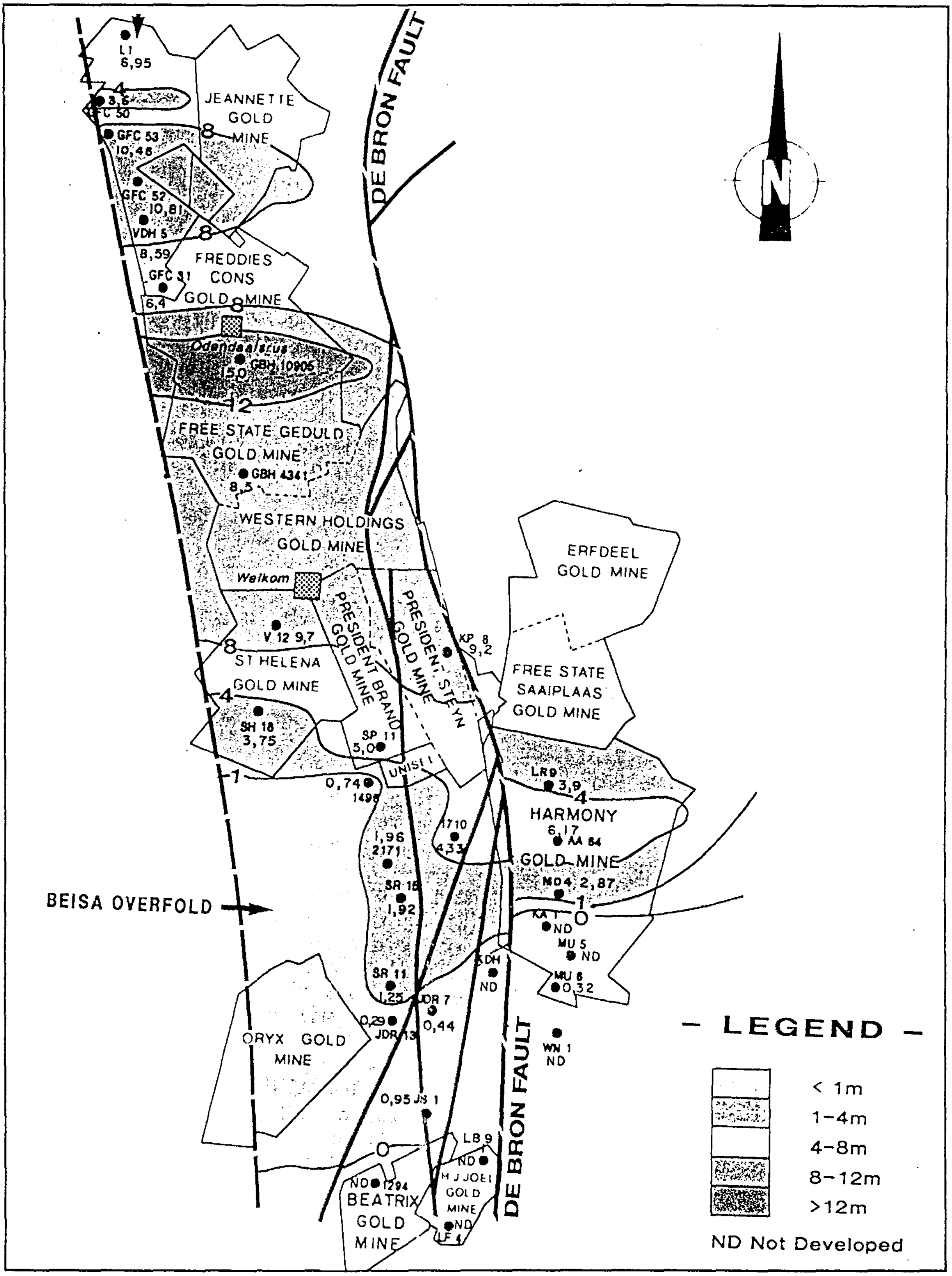


Figure 8 *Isopach of the Big Pebble Marker (after van Biljon, In Ellis, 1991)*

The zero isopach of the BPM trends east-west just to the north of Beatrix Gold Mine in the Odendsaalsrus section and through the southern part of Harmony Gold Mine in the Virginia section.

In the northern portion of the OFS Goldfield the BPM can be divided into two facies. These facies are very prominent on Loraine Gold Mine and less so on Harmony Gold Mine. The lower facies is generally a polymictic, matrix-supported, coarse pebble conglomerate which becomes progressively more clast supported to the south. An upwards fining sequence is common. Geologists on Loraine Gold Mine believe that this facies could represent the waning phase of Spes Bona sedimentation (van Biljon; in Ellis *et al.*, 1991). The upper conglomeratic facies is essentially a clast- supported, oligomictic, medium pebble conglomerate which fines upwards. On Loraine the Upper BPM is erosive and in places eliminates the underlying polymictic facies. Laterally this facies is fairly persistant, although, in some of the boreholes in the central part of the Welkom Goldfield, it is not as evident. Overlying the BPM is a siliceous quartz arenite known as the Glassy Marker. This very useful marker is very clear on Loraine but becomes more difficult to recognise towards the south.

In the southern portion of the Welkom Goldfield the Upper BPM is locally known as the Kalkoenkrans reef (Genmin), Sandrivier reef (GFSA) or Aandenk reef (JCI). The thickness of the BPM decreases from north to south where, in boreholes JDR7, JDR13 and JS1, it occurs as a single conglomerate band (van Biljon; in Ellis *et al.*,1991). South of borehole JS1 the BPM subcrops against the VS5 Reef.

Overlying the A Reef is the *Earl's Court Member* which consists of alternating successions of quartzwackes, polymictic and oligomictic conglomerates(van Biljon; in Ellis *et al.*,1991). The polymictic conglomerates are more common and are generally matrix supported with small to coarse sized pebble clasts. The associated sediments are generally medium to coarse-grained quartzwackes with scattered pebbles. Occasionally the matrix of the oligomictic conglomerates is more siliceous.

The Earls Court Member is better developed towards the north. To the south the percentage of conglomerate and the thicknesses thereof decreases. Correlation of individual conglomerate horizons is very difficult. Several authors have made mention of a Transition Zone at the top of the Kimberley Formation. Borchers (1950) calls this zone the T1 Zone, which he says can be 15 metres thick. Mouton (in Ellis *et al.*, 1991) describes the transition zone as a submature khaki/grey zone which occurs locally in the immediate footwall of the Eldorado Formation. These quartzites appear to be a hybrid between typical yellowish Aandenk quartzites and the more greyish quartzites associated with the base of the Eldorado Formation.

At Harmony Gold Mine, isopachs of the Earl's Court Member indicate a patchy distribution confined to the northwest (Fig.9). The patchy distribution is due to the undulating nature of the Eldorado unconformity and the infill of palaeo lows. The areas of thicker deposition are found in close proximity to the viable 'A' Reef areas (Fig.9). This would indicate that the viable 'A' Reef areas represent possible palaeo lows. The Earl's Court Member is truncated towards the south and east of Harmony mine by the Eldorado Formation (Swart,1992).

Cross-bedding was measured in the Earl's Court quartzites at 6 sites on President Steyn, 3 on President Brand and 2 on Welkom (Sims,1969). The total sampled coverage involved 96 cross-bed units at the 11 localities. The evidence from cross-bedding indicates that the direction of transport was essentially from west to east. The rose diagrams are essentially of a unimodal character (Fig.10).

Eldorado Formation. The Eldorado Formation is a wedge-shaped sequence of fanglomerates and arenites which thickens from 200m in the west to 600m in the east over a distance of 5km. Kingsley

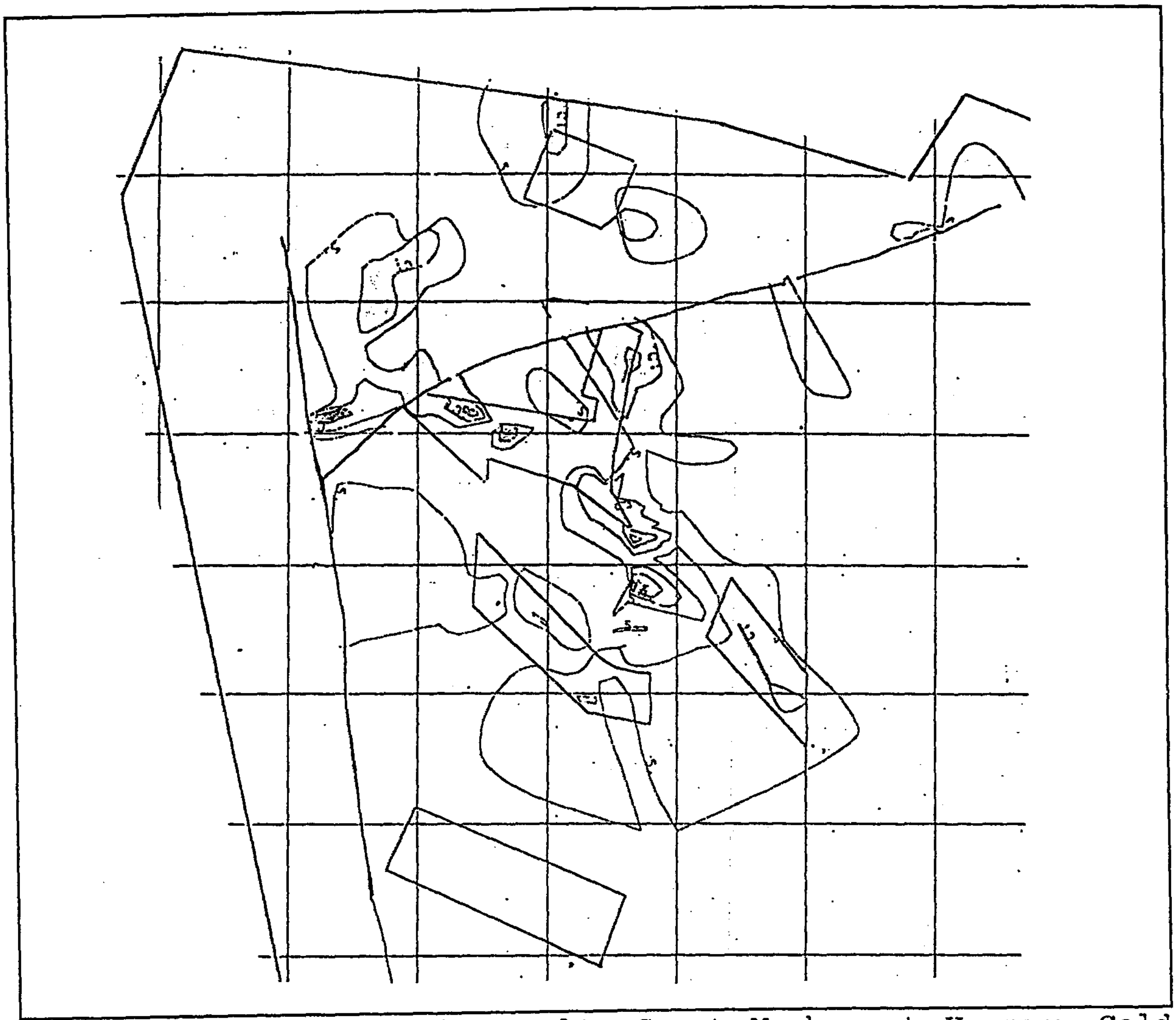


Figure 9 Isopachs of the Earl's Court Member at Harmony Gold Mine(after Swart, 1992).

(1987) recognises four different sedimentary cycles in the Eldorado Formation in the Welkom Goldfield, namely the"ED" zone (Rosedale Member), the"EC-EB" zone (Van den Heeversrust Member), the "EA" zone, and the Uitkyk Member, each varying between 100m and 150m in thickness (Fig.11). Two distinct facies are recognised, one in the north (the Loraine facies), which is predominantly quartzarenite and the other in the south (the Welkom facies) which comprises mainly litharenite and subgreywacke.

The base of the Eldorado Formation is marked by a major unconformity that extends across the entire Welkom goldfield, the VS5 unconformity. Associated with this unconformity is an

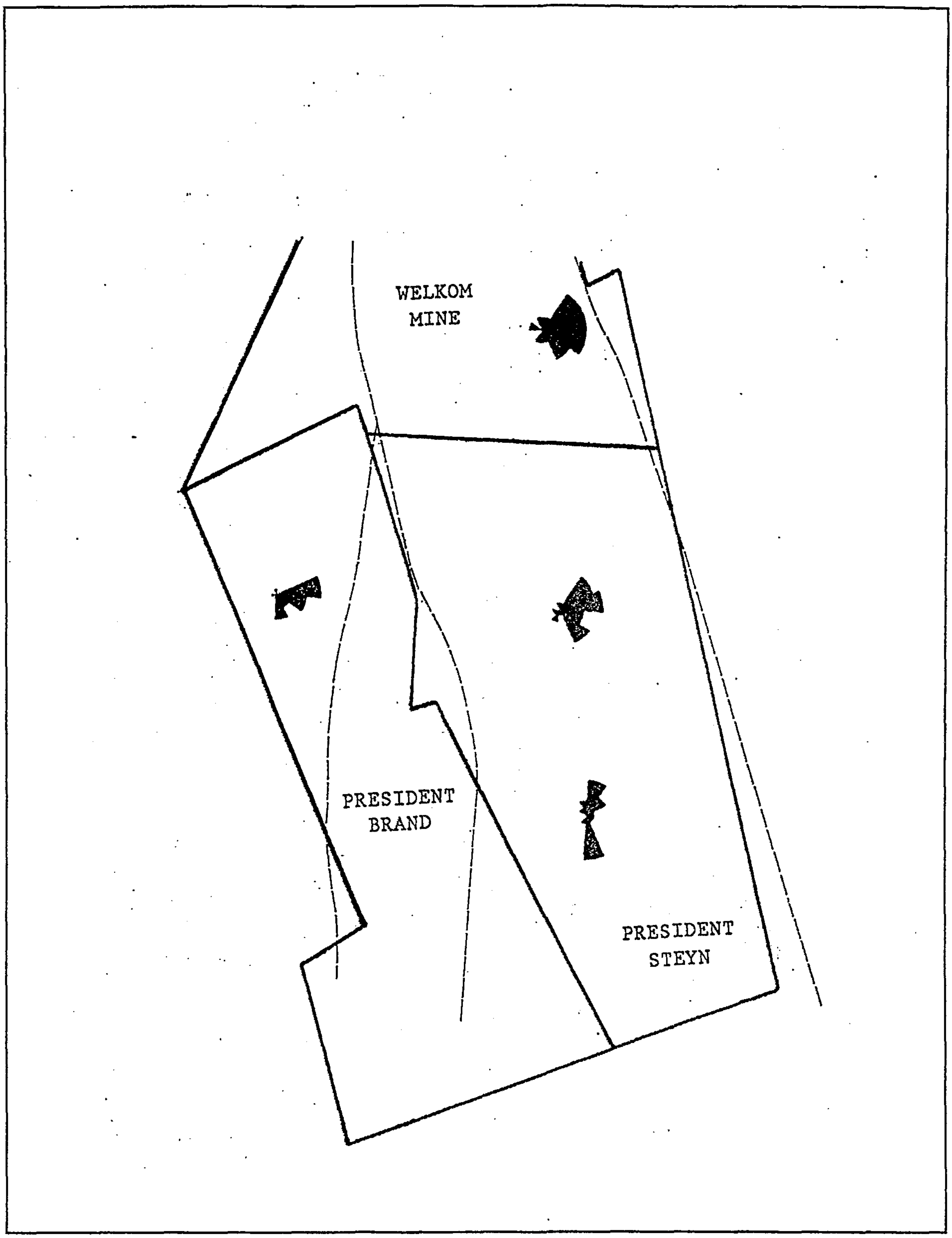


Figure 10 *Cross-bedding in the Earl's Court and Eldorado quartzite (after Sims, 1969).*

oligomictic small pebble conglomerate called the Eldorado Basal Conglomerate, which Winter (1957) called the "Gold Estates Leader" and which, in the Virginia/Merriespruit area, lies on a channel shale. Swart (1992) states that the "EBC" contains isolated values but becomes payable where it truncates the "A" Reef Zone, as in the south of Harmony mine. East of Harmony Gold Mine in the downthrown Central Rand Group sediments to the east of the Virginia fault (an area known as the G.F. Block) the sedimentary break represented by this disconformity is extensive. Here the "EBC" has transgressed the Big Pebble Marker, the "B" Reef and Leader Reef disconformities until, in the far south, the "EBC" directly overlies quartzite of the St Helena Formation (Winter,1964).

Above the "EBC" lies a polymictic conglomerate known as the VS5 (Winter,1957) or Rosedale placer (Kingsley,1987). The Rosedale conglomerates are intimately associated with facies changes. They interfinger northward, eastward and southward with the overlying arenites and grade into grit and arenite. The Rosedale placer, is a polymictic cobble conglomerate or a pebbly quartzite as much as 5m thick in the

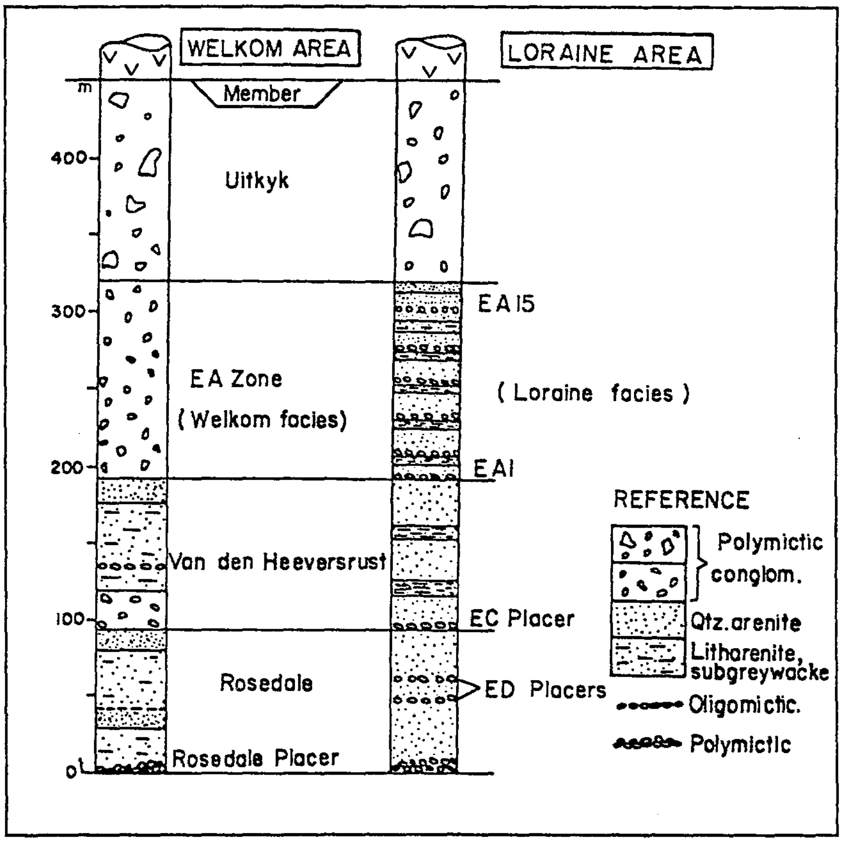


Figure 11 Stratigraphic subdivision of the Eldorado Formation showing its main lithologies (after Kingsley, 1987).

proximal area grading into a medium and small pebble conglomerate 1m thick or less, 15km down the palaeoslope. Clasts are poorly sorted. Quartz rarely exceeds 25 percent of the pebble population but increases relative to the other components downslope because the nondurable clasts were destroyed during abrasion. At some localities the lower 1m of the Rosedale placer was sorted texturally, thereby upgrading it to a litharenite, and in some cases a quartz arenite. As a result of this sorting, concentration of some heavy minerals such as pyrite, gold and uraninite took place. In the Welkom area the Rosedale Member may be subdivided into two units, the lower one being dark grey and siliceous with siltstone drapes on top of thin sedimentation units. Crossbedding is conspicuos. The colour changes in the overlying unit to slightly yellowish-grey as a result of an increase in the pyrophyllite matrix but toward the top, grey quartzarenites dominate again. Gritty material is very common in the upper part of the unit.

The basal conglomerate of the Van der Heeversrust Member rests disconformably on the Rosedale Member. The lower part of the Van den Heeversrust Member consists of a typical conglomeratic to subgreywacke sequence. The robust conglomerate changes within 5km downfan into first a sequence of conglomerate/arenite units and then into an arenite sequence with only a few pebble lags which grade into grits beyond the limit of the conglomerate fan. Trough cross-bedding is ubiquitous.

A marked change occurs at the base of the EA zone throughout the area, especially near the proximal western edge.There is also a marked lithological change within this zone between the Welkom facies and the Loraine facies. The proportion of polymictic conglomerates decreases (90 percent to 50 percent) at Loraine with an increase in subgreywacke beds. Some small pebble oligomictic conglomerates and quartzarenites make their appearance as intercalations in the immature sequence. The oligomictic conglomerates contain heavy mineral and gold concentrations, which is the main reason why the EA zone is economically viable in the Loraine facies, whereas its correlative in the Welkom facies is not.

In the proximal area the typical boulder beds of the overlying Uitkyk Member are difficult to distinguish from the massive conglomerates of the EA zone. Southward and southeastward from the proximal area, the boulder beds of this member change facies very rapidly over 4.1 km from a robust cobble and boulder conglomerate to a litharenitic facies. In distal positions, such as on Beatrix Gold Mine, Erfdeel Gold Mine and Jeannette Gold Mine, the Uitkyk Member and the EA zone both change into a sandy sequence and distinction between them becomes more difficult (Kingsley,1987).

The relationships between the VS5 unconformity at the base of the Eldorado Formation and the underlying formations are depicted in Fig. 12. The map shows that the Eldorado Formation gradually transgresses the Kimberley Reefs, and eventually, the Leader Reef in the G.F. Block, finally coming to rest on Middle Footwall Beds to the south and southeast of the mines.

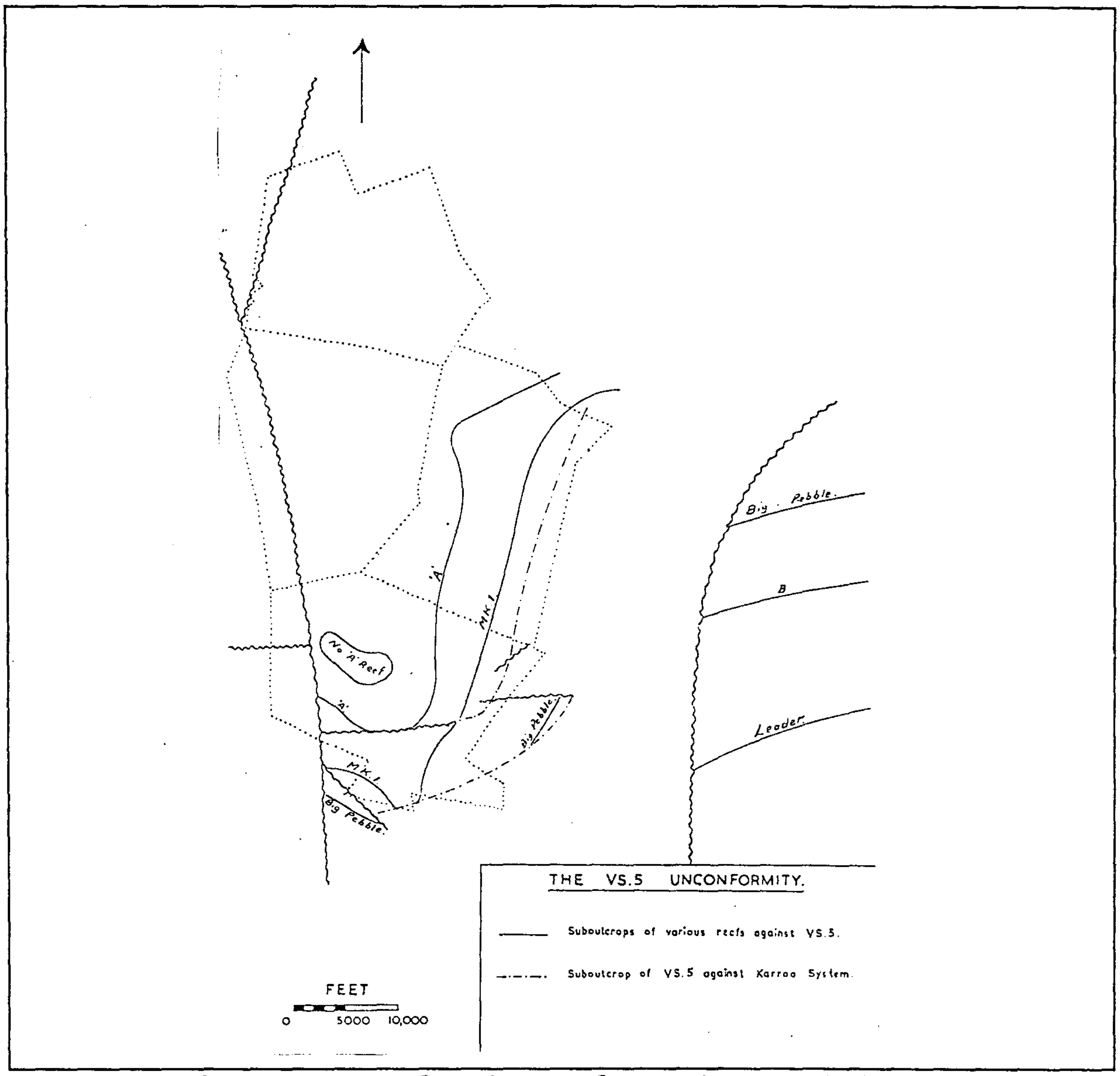


Figure 12 The VS5 Unconformity (after Winter,1964).

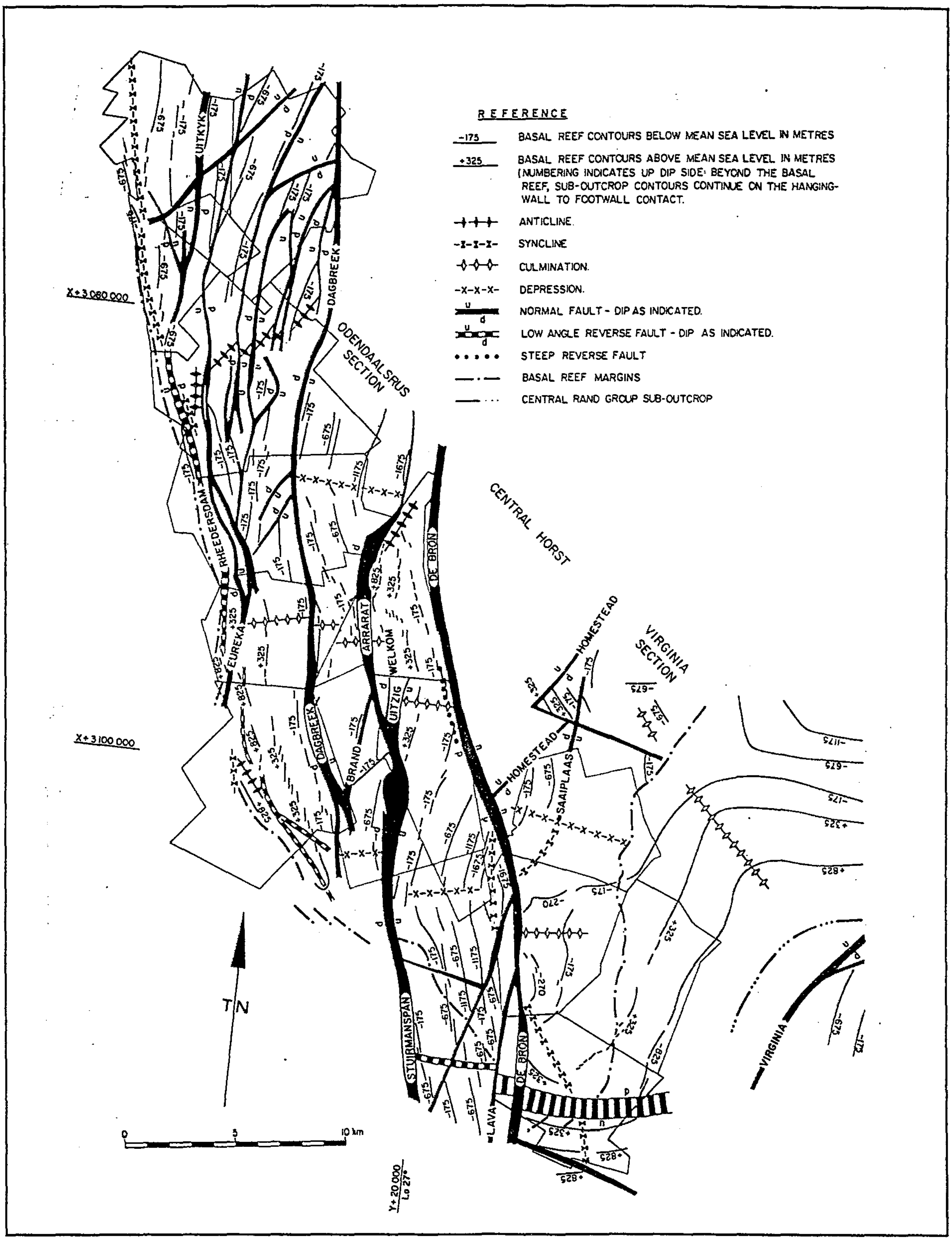


Figure 13 Structural plan of the Welkom Goldfield showing contours of the Basal and Steyn placers and the faults and folds that affect the palaeosurface (after Minter et al.,1986).

4.Structure

The Witwatersrand Supergroup in the Welkom Goldfield constitutes a faulted and eroded syncline, widening northwards, as its axis pitches to the north (Fig.13). This synclinal structure is split near its axis by two major faults. These two faults, the De Bron and the Homestead, form a triangular-shaped Central Horst block that structurally divides the goldfield into a western, Odendaalsrus, section and an eastern, Virginia, section. To the east of Harmony Gold Mine a portion of the eastern limb of the syncline has been dropped down east of the Virginia Fault in a reef-bearing block of ground which is known as the G.F. Block.

4.1 Folding

The major syncline axis trends north and is displaced by the De Bron Fault (Fig.13). From Merriespruit, where it lies to the east of the De Bron Fault, it crosses to the west between Video and Harmony, and then returns to the east, where it is defined by an abrupt change in the dips of the Central Rand Group, from easterly to westerly, coinciding with the Saaiplaas Fault. Minter et al.(1986) state that the the fold structure is not molded on the original sedimentary basin geometry as was thought by Winter (1964) but that the stratigraphic convergence of the Eldorado Formation and the Basal Reef, to the east of the syncline, is the result of sedimentary thinning and that the depository is open to the east.

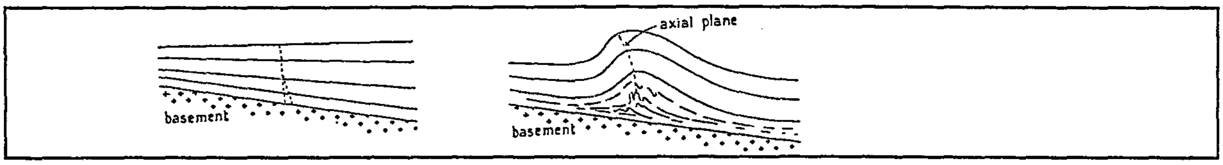


Figure 14 *Asymmetric fold on basin margin due to thinning of sedimentary series (after De Sitter,1964).*

The Virginia Section - Close to the axis of the syncline the dips are very gentle ($\leq 5°$) whereas towards the sub-outcrop the dips

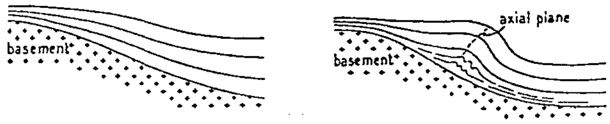


Figure 15 *Asymmetric fold on basin margin due to higher elevation of basin order (after De Sitter,1964).*

increase to about 15°. Winter (1964) believes that this indicates that the folding is therefore merely an accentuation of the warping of the basin whilst it is receiving sediments. A major anticlinal fold is present on the southern boundary of the Merriespruit Thrust Fault which Winter (1964) believes culminated in the thrust fault. De Sitter (1964) describes how assymmetric folding can occur due to i) wedging out of a folded series (Fig.14), and ii) original differences of altitude between two flanks of the same fold (Fig.15), two situations that may have existed in the case of the Merriespruit Thrust Fault. Further lateral compression will then result in thrusting taking place due to space problems occurring at depth during the concentric folding. A similar monocline 2750m to the north on the western side of the De Bron Fault is probably the same monocline that has been shifted laterally by the movement on the De Bron Fault.

The G.F.Block - The Witwatersrand strata in the G.F. Block have an average dip to the west of 32°, being the eastern limb of the syncline that has been downthrown by the Virginia Fault. The A-reef and the B-Reef and Leader Reef subcrop against the Eldorado Formation in this block. These subcrop positions strike north-northeastwards almost parallel to the Virginia fault.

The Odendaalsrus Section - This section lies to the west of the De Bron fault and extends from Loraine mine in the north to Beatrix and Joel mines in the south (Fig.1). Figure 16 shows a section drawn from west to east from St. Helena Gold Mine through President Brand and President Steyn Gold Mines to Free State Saaiplaas Gold Mines.

The structure in this area is complex , but in its simplest form

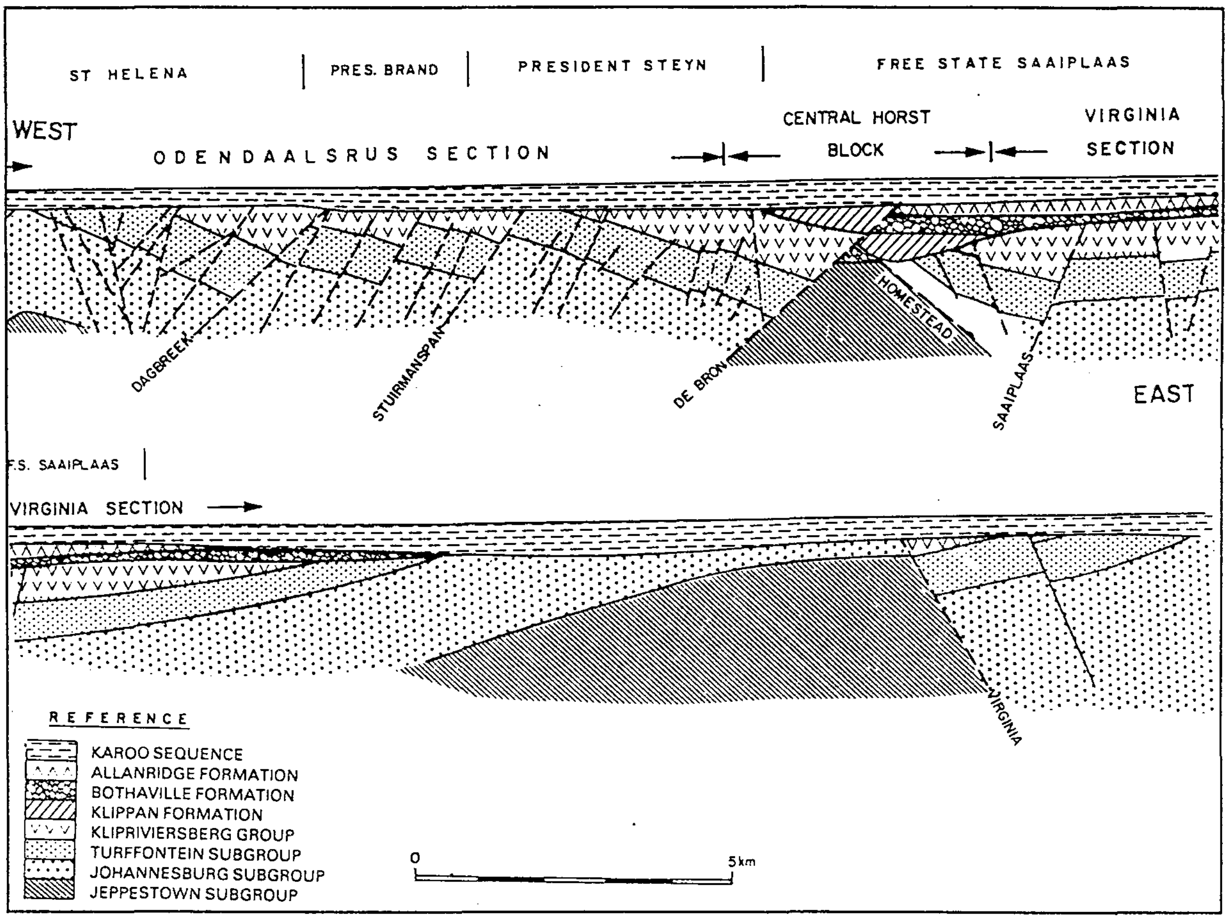


Figure 16 *Structural section from west to east through the Welkom Goldfield (after Minter et al.,1986)*

it consists of several normally down-faulted blocks of the western limb of the syncline with the bedding dipping to the east (Fig.16). The western margin of the goldfield is defined by an overturned syncline that extends from Loraine Gold Mine in the north to Oryx Gold Mine in the south.

4.2 Faulting

Minter *et al.*(1986) have divided the faulting in the Welkom Goldfield into three events. These are the Central Rand Group events, Late Klipriviersberg and early Platberg events, and post-Ventersdorp events.

Central Rand Group events - Two types of faulting of Central Rand Group Age have been identified. The first are thrust and slump faults which are said to to have formed contemporaneously with sedimentation and secondly reverse faults (e.g. Rheedersdam Fault) which it is suggested , formed sympathetically with the western margin fold (Minter *et al.*,1986). Both types of faulting are confined to the western margin of the goldfield, and their temporal relationship with the final stages of the Central Rand Group deposition is indicated by sedimentary responses which are reflected mainly in the Eldorado Formation.

Late Kliprivierberg and early Platberg events - The predominant structures formed by these events are the main strike faults in the goldfield: the De Bron; the Arrarat and Stuirmanspan; the Homestead; and the Virginia. The commencement of this event is dated as late- or post Klipriviersberg, because the De Bron, Homestead, Arrarat and Eureka fault planes produced geomorphic scarps and valleys which became Platberg group depositories.

Post-Ventersdorp events - The major strike faults, in particular the De Bron and Homestead, were re-activated after deposition of the Pniel Sequence (the uppermost part of the Ventersdorp Supergroup).

In the Welkom goldfield the following faults dominate the pre-Karroo structure:

i) The De Bron Fault- The De Bron Fault cuts across the horizon of the Basal Reef near the western boundary of Harmony Gold Mine and the Eastern boundaries of the President Steyn and Welkom Mines. It is probably a fault zone, with the earlier faulting not confined to a single fault plane, and the subsequent movements need not have been superimposed on the fault-planes formed first. Coetzee (1960) states that faulting occurred in two stages. During the first stage of the faulting the eastern block was elevated and subjected to erosion. Most of the Central Rand Group strata were eroded from the horst block before the Bothaville Formation of the Ventersdorp Supergroup was deposited. During the second phase of the faulting, which occurred when part of the

Platberg Group had already been deposited, the eastern block dropped down and juxtaposed the Klipriviersberg and the Platberg Group along the eastern boundaries of the Welkom and President Steyn Mines. Coetzee (1960) states that the former movement was attended by a throw of about 2440m and the latter by a throw of about 610m. Myers *et al.*(1990) state that there has been 4700m right-lateral movement and 1100m downthrow to the west on the De Bron fault.

ii) The Stuirmanspan Fault- Myers *et al.*(1990) state that there is right-lateral displacement of 1500m and 1100m downthrow to the west along the Stuirmanspan fault.

iii) The Homestead Fault- The movement of the foot-wall block of the Homestead Fault simulates the movement of the same block on the De Bron Fault (Coetzee,1960) : a relative upthrow of the Witwatersrand strata and the Klipriviersberg Group was followed by erosion and later by a relative downthrow during, or subsequent to, the deposition of the younger Platberg Group rocks. Borchers (1950) states that the Homestead fault has a downthrow to the west, causing a displacement of the Pniel Sequence of 400m.

iv) The Virginia Fault- The Virginia Fault is a N.E.-S.W. striking normal fault to the south of Henneman with 1525m downthrow to the east (Coetzee,1960).

v) The Merriespruit Thrust Fault- The Merriespruit Thrust Fault strikes in an east-west direction across the southern part of Harmony Gold Mine and dips to the east. It terminates against the De Bron Fault to the west, and seems to fade out to the east. Coetzee (1960) states that the strata to the south have experienced an upthrow of roughly 610m.

vi) The Erfdeel-Whites Fault- A major normal fault strikes in a south-southwesterly direction from north of Free State Saaiplaas mine to just north of Whites. The Central Rand Group beds which suboutcrop below the Karroo sediments are cut off against the fault and brought into juxtaposition with the Platberg Group rocks. The Witwatersrand reefs and the bottom contact of the Platberg Group have been downthrown on the northern side of the fault and so the the fault originated during or after the deposition of the Platberg Group rocks.

5. The "B" Reef Zone

5.1 Lithology

The"B" placer lies at the base of the Spes Bona Formation or is separated from the base by a few centimetres of fairly pure quartzite (The Doornkop Quartzite). The oldest placer sediments are dark grey oligomictic conglomerates that are preserved only in the cores of some channels,whereas the younger "B" placers are more polymictic with the arenite containing a more argillaceous matrix. These younger polymictic "B" placers contain on average 60% vein quartz, 9% chert, 1% quartzite, 4% quartz-porphyry, and 26% yellow shale (Minter,1978). Winter (1964) in his description of the "B" reef pebbles at Harmony Gold Mine describes a decrease in packing density from the base of the reef upwards, poor sorting, poor rounding, and a variety of shapes. Some of the bands contain an abundance of yellow, partly silicified sericitic shale pebbles. Many of these are lath-shaped or discoidal, others are compressed between harder pebbles. The matrix is less sericitic than the quartzite overlying the "B" Reef.

Fann (in Ellis *et al.*,1991) states that the B Reef varies in nature over the Loraine lease area. It is generally represented by two or three polymictic, matrix supported , medium-pebbled horizons, separated by coarse grained quartzwackes.

5.2 Facies Types

On Loraine Gold Mine, the "B" placer consists of three facies, called B1, B2 and B3. These are shown in figure 17. The following descriptions are taken from the Mullins *et al.*(1986,p34) :

"Facies B1 is found in narrow (less than 15m) channels seldom more than 1m deep, and are filled with thin, oligomictic gravel lags overlain by planar cross-bedded siliceous sands, and occasionally by conglomerates. Kerogen is present as "flyspeck" grains. Facies B1 appears to be the localized remnants of a large channel system flowing from the south.

Facies B2 unconformably overlies facies B1 and comprises thin gravel lags, gravel bars and gravel and sand filled channels. Kerogen is present as seams and in the conglomerate matrix. The palaeocurrent direction is from the south.

Facies B3 varies from a thin pebble lag to a 3m thick

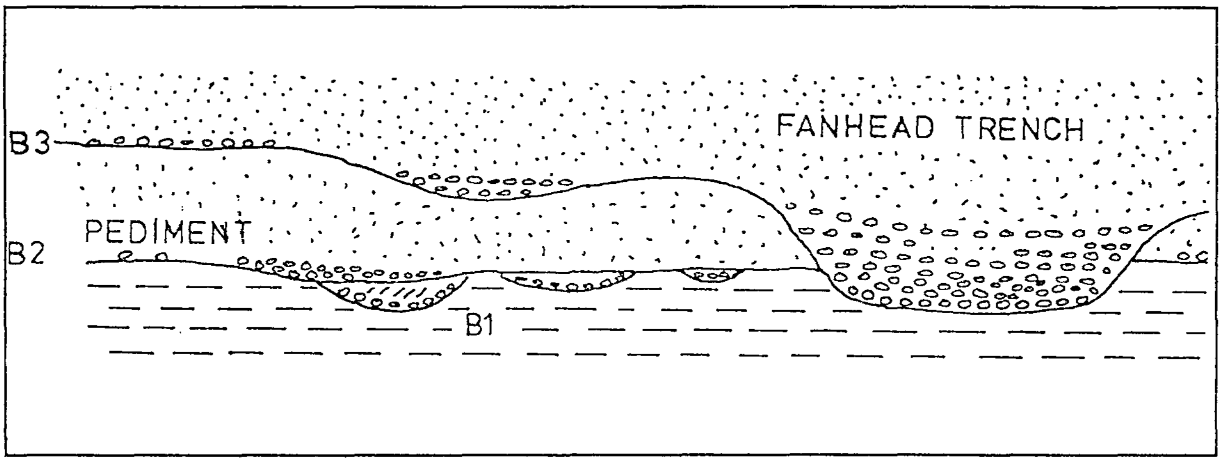


Figure 17 *Relationship of facies B1, B2 and B3 in the "B" placer horizon (Mullins et al,1986).*

conglomerate sequence. Thick conglomerate units fill incised channels (Fig 17).

5.3 Channel Morphology

Minter (1978,p531) describes the "B" placer as "being confined to discrete, interconnected channels. The channel profiles are seldom symmetrical (Fig. 18), but generally show one steeply inclined side and an opposite low-angled side. The channels were not filled sideways, as by pointbar migration, but rather symmetrically. Transverse bars of avalanche-bedded pebbly sand and longitudinal bars of gravel grew down the channels and spread laterally. In some instances gravel accumulations appear to hug one side of the channel. The placer channelways range in width from 1 to 200m and are up to 2m deep. They are shallower in

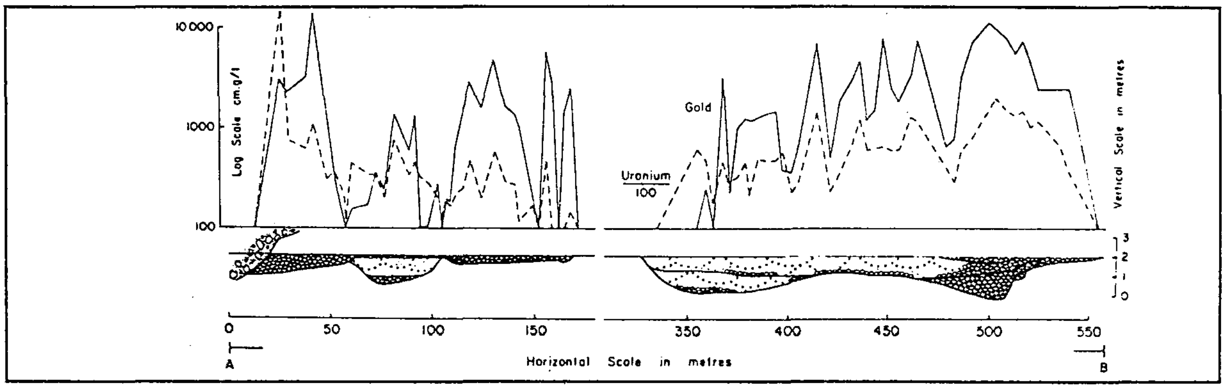


Figure 18 *A section drawn in the northern part of the Welkom Goldfield to illustrate that channel sediment of the B placer and associated gold and uranium mineralization is confined to channelways (after Minter,1978).*

distal locations". Minter (1978) states that the channels meander in a braided pattern that bifurcates and joins.

Minter (1978) states that the proportion of the Spes Bona palaeosurface covered by B placer channels is generally less than 35 per cent. These channel sediments comprise coarse-grained pyrite and pebble lags on scour surfaces, longitudinal gravel bars and trough cross-bedded siliceous quartzites. On the basis of these facies Minter (1978) has related the proximal facies of the B Reef to a Donjek braided river model and the distal facies to the Platte braided river model as described by Miall (1977). Victor (1990) however describes the "B" Reef at Free State Saaiplaas No 5 Shaft as occurring either as a tabular (or thin lenticular) body with a diffuse upper contact or as conglomeratic infills of shallow depressions in the surface of deposition. Fann (in Ellis *et al.*,1991) states that the channelling of the "B" Reef at Loraine Mine is not severe and generally of a wide and relatively shallow nature.

5.4 Directional Structures

Sims (1969) in a study of pebble types and sizes (a-axes of 25 largest pebbles) done at President Brand, President Steyn and Free State Saaiplaas mines showed that:

i) The pebble sizes decreased from a mean size of 125mm at the No. 2 shaft at President Brand to 60mm at the No. 2 shaft at Free State Saaiplaas.
ii) The percentage of durable pebbles decreases from 77,1% at President Brand No 2. shaft to +- 55% at President Steyn to 33,6% at No.2 shaft Free State Saaiplaas mine.

The indicated palaeocurrent direction is from south west to north east. Minter (1978) obtained palaeocurrent vectors indicating a northeasterly vectoral mean. Further evidence for the influx of the B Reef from the west is given by Winter (1964a) who shows that there is a sharp truncation of the "B" Reef on the western side of Loraine Gold Mine. He states that during these times, the land to the west was actively rising which, together with the greater thickness towards the southwest, points to a sediment influx mainly from the west.

As can be seen from the isopach plan (Fig.19) the B reef reaches a maximum thickness of nearly 6 metres in the Freddies Cons and Free State Geduld gold mine areas. To the north and south of this area it thins until it subcrops in the northern parts of Loraine and Jeanette gold mines in the north and just north of Oryx gold mine in the south. To the east of the De Bron fault it reaches a maximum thickness of slightly over 4 metres in the Merriespruit section of Harmony gold mine. South of this it thins dramatically until it subcrops just to the south of Harmony gold mine. To the north it decreases and then increases in thickness towards Free State Saaiplaas Gold Mine.

5.5 Gold and Uranium Distribution

The "B" placer is economic only on Loraine, Free State Geduld and Free State Saaiplaas mines (Minter *et al.*,1986; Victor,1989). At Loraine Mine , stoping on the "B" Reef is confined to the No.2 Shaft area (Winter,1964a). Winter delineated an area there of "B" Reef some 2135m long by 1220m broad which was sufficiently rich in gold to be mineable. This area is elongated in the direction

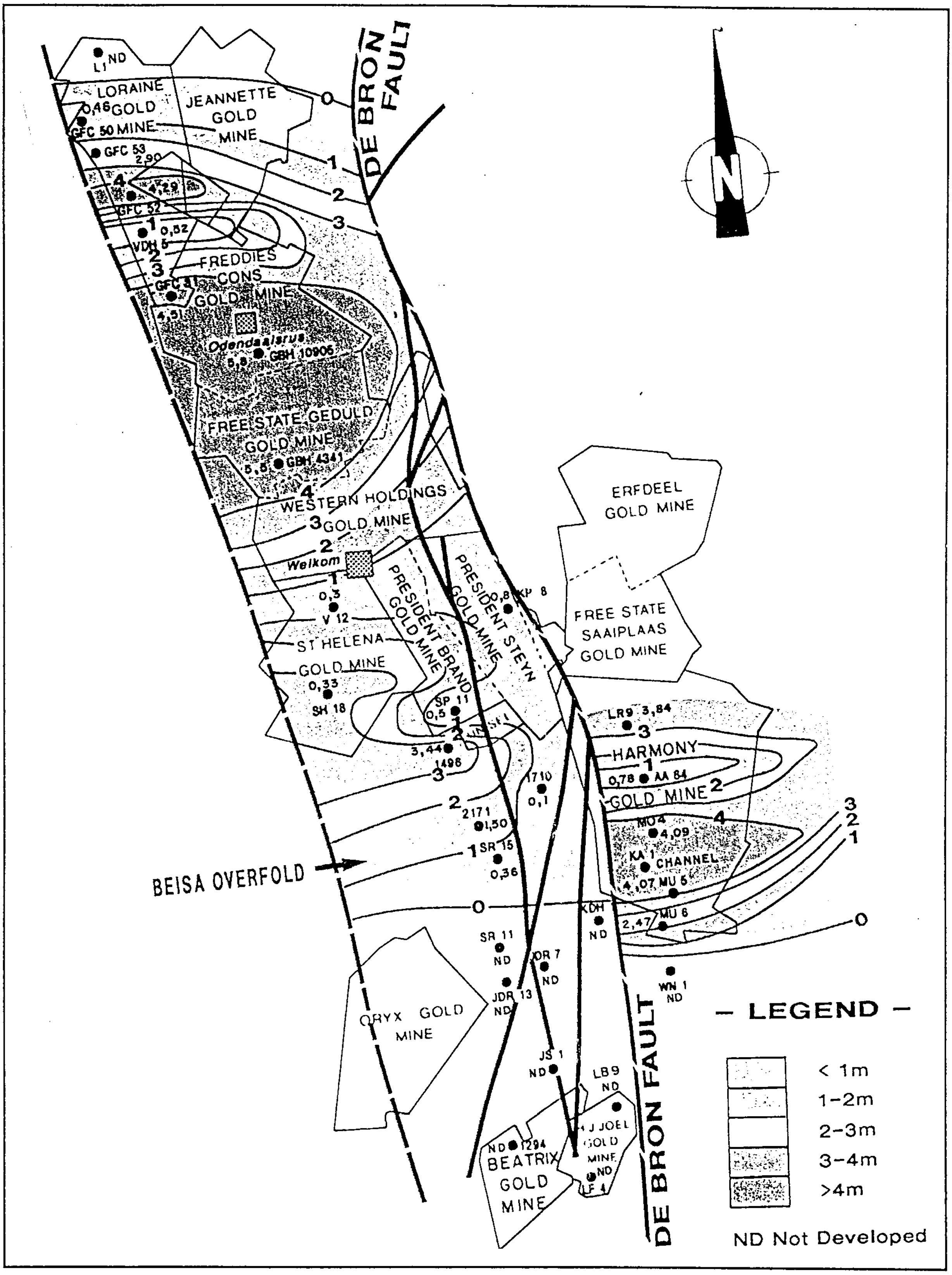


Figure 19 *Isopach of the B Reef Zone (after van Biljon, in Ellis, 1991)*

N35E. The gold is patchily distributed and is concentrated in isolated lenses of columnar thucolite. In these patches the reef is remarkably rich. Block plans show that uranium values decrease downdip.

In the Virginia and Merriespruit sections at Harmony mine Winter (1957) describes the mineralization as sporadic. He emphasises the point that it is the oligomictic portions of the "B" placer that are mineralised. Fairly large rounded "buckshot" grains of pyrite (up to 10mm in diameter) and "carbon" specks can be seen in the gold-bearing portions of the reef, those being usually found near the base. The "B" Reef has promising gold values in the south-eastern part of Merriespruit Mine, where the disconformity below the reef is more pronounced than elsewhere (Winter,1957). Minter *et al.*,(1986) state that the carbon layer is usually preserved only in distal parts of the basin. In channels, the reef is well mineralized with coarse-grained pyrite (Fig 18).

5.6 The "B" Reef Unconformity

The basal contact of the B Reef is a regional unconformity and can be traced throughout the basin. Winter (1957) describes the following features (Fig 20) of the B Reef disconformity at Harmony gold mine:

(1) The "B" Reef transgresses the Leader/Basal Reef south of the Merriespruit Mine but is overlapped by the VS5 before transgressing the Leader Reef in the G.F. Block.

(2) Reef in cores of boreholes west of the De Bron fault in the Virginia-Merriespruit area have not been definitely correlated with the "B" reef. It is therefore highly probable that the "B" Reef is not developed west of Harmony Mine, or that it is transgressed by the Big Pebble Reef.

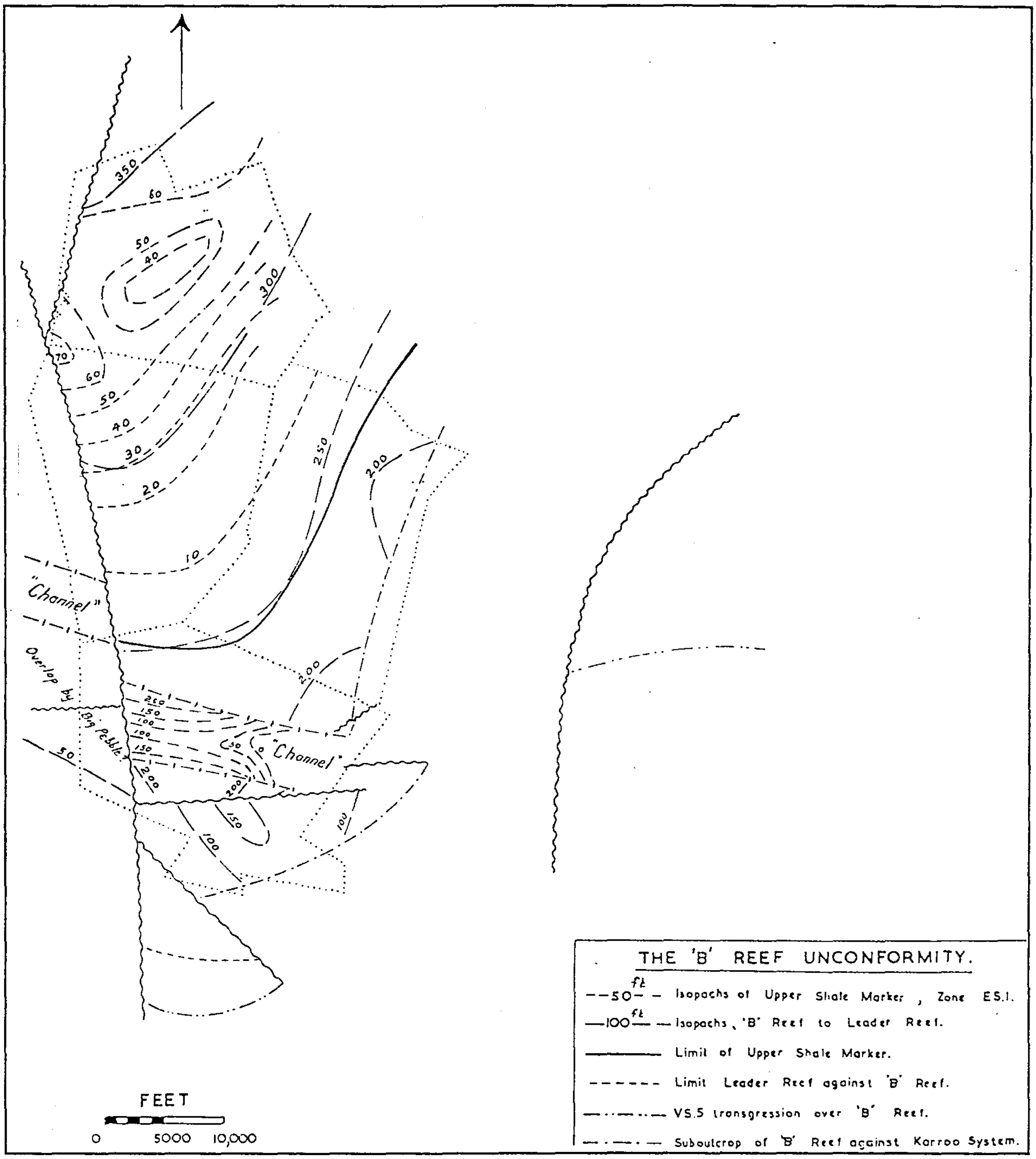


Figure 20 *Isopach map of the thickness of strata between the base of the "B"Reef and the base of the Upper Shale Marker, and from the base of the "B"Reef to the base of the Leader Reef(after Winter,1964).*

6. The "A" Reef Zone

Until recently, information related to the "A" Reef in the O.F.S. Goldfield was limited. Two detailed reports however have recently been produced by Blamey (1991) and Swart (1992) on the "A"-Reef at Western Holdings and Harmony Gold Mines respectively. Other contributions have been reports by Jordaan, Bailey *et al.*, Rogers, Davies and Hatherly, and Grobler at an O.F.S. Goldfield symposium (1989) and reports by Jordaan, Fann, Ellis, Mouton, van Biljon and Davies in an unpublished combined Aandenk - Spes Bona workshop report.

The A-reef in the Welkom Goldfield has received minor attention in the history of the Welkom Goldfield until the early 1980's. The "A"-Reef was first exploited on President Steyn and Free State Geduld mines (Blamey,1991). At Harmony Gold Mine minor haulage development on 11 level and regular spaced diamond drilling on the "A" Reef was undertaken in early 1964. In September 1964 the 11-12b raise commenced developing on reef. The results were poor and the programme was called off (Swart, 1992). It was only in November 1982 that diamond drilling for the "A" Reef started again, with haulage development moving south and north from Harmony No 2 and 3 shafts in 1985 and 1986 respectively. Exploration on the "A"-Reef on Western Holdings Mine was initiated during 1980. Encouraging gold values from the drilling and reef development led to the decision to exploit the Witpan Placer on No.3 Shaft as a low-cost mining exercise (Blamey,1991). Figure 21 shows the areas in which "A"-Reef has been mined in the Welkom Goldfield up to the end of 1991.

6.1 Reef Types

The "A" reef is generally described as being a reef couplet consisting of two placers, the Witpan and the Uitsig. These two placers are present in much of the Central part of the OFS Goldfields and in the northern part of Harmony Gold Mine. To the north at Loraine mine the Witpan and Uitsig placers have not been individually identified in the" A"-Reef interval (Jordaan,in Ellis *et al.*,1991).

On Harmony Gold Mine Swart (1992) includes the underlying "Reworked BPM" and the overlying "Hangingwall grits" and Upper "A" Reef into the "A" Reef Zone. He divides the A-Reef Zone into three stratigraphical horizons namely the Lower, Middle and Upper "A" Reef placers. The "Reworked BPM" and the Witpan placer are included in the Lower "A" Reef and the Uitsig placer and the "HW Grit" granule conglomerate in the Middle "A" Reef placer. The Upper "A" placer is called the "HW Marker" on AAC mines. These five different placers are shown in figure 22.

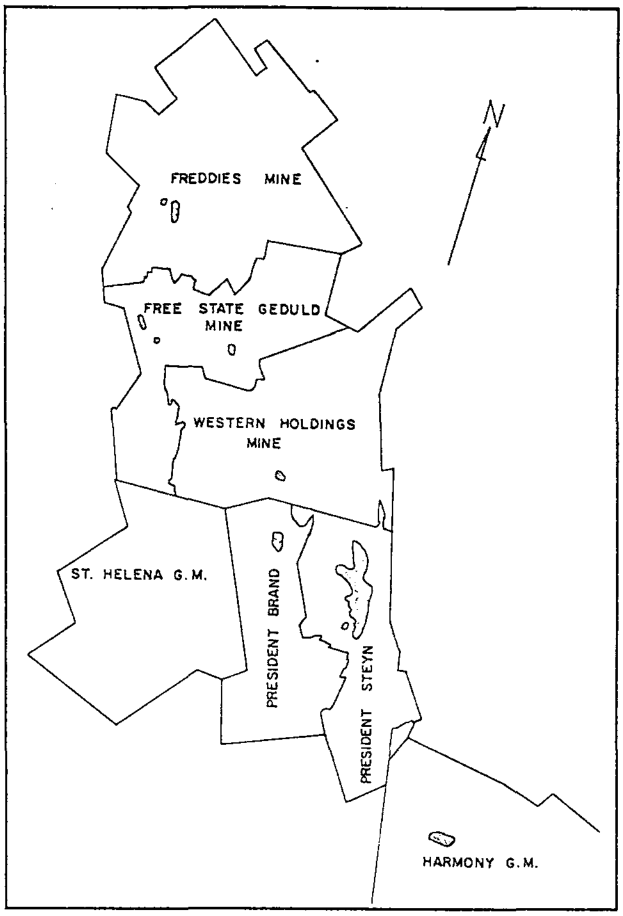


Figure 21 *Locality map showing areas in which "A" Reef has been mined in the Welkom Goldfield. The areas are coloured in yellow (after Blamey,1991)*

Reworked BPM - The Reworked BPM consists mainly of massive conglomerates interbedded with minor matrix-supported conglomerates and trough cross-bedded quartz arenites. These facies fill "channels" or scours that generally strike in a north-west to south-east direction. The "channels" form steep sides and contain massive to multiple upwards fining conglomerate cycles. The areas between "channels" consist of single band to lag conglomerates (Swart,1992). Swart (1992) shows that the thickest Reworked BPM at Harmony Gold Mine is found in areas with the thinnest BPM. At Harmony Mine the conglomerates and arenites in the uppermost interval of the Big Pebble Marker are considerably more mature than those in the underlying unit over much of the area, and mineralized locally to the extent that it becomes minable. At an Aandenk-Spes Bona workshop (Ellis *et al.*,1991) there were suggestions by various company geologists that the "Reworked BPM" could be correlated with other reef horizons in the area. These are Big Pebble Reefs on Lorraine Gold Mine, the Kalkoenkrans Reef on Oryx Gold Mine, Sand River Reef on Doornrivier (GFSA), the Aandenk Reef (JCI) and the K2 or K4 Reefs (AAC). Consensus was not reached on this however.

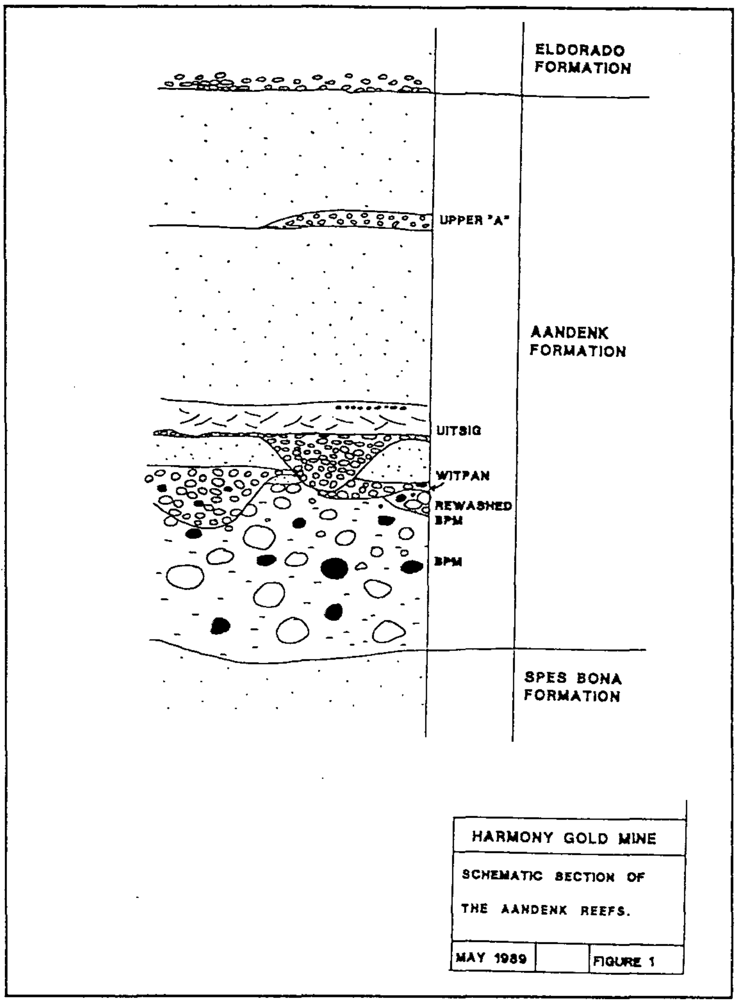


Figure 22 *Schematic section of the "A" Reef zone (after Davies and Hatherly, 1989).*

Mouton (in Ellis *et al.*,1991) believes that the Sand River Reef pre-dates the Rewashed BPM (Upper BPM).

The bottom contact of the Reworked BPM is marked by a regional unconformity. The underlying formations are truncated towards the south of Harmony mine. In turn the Reworked BPM is truncated by the EBC of the Eldorado Formation just north of Joel and Beatrix mines. Isolated remnants of Reworked BPM are found in the northern parts of Joel and Beatrix, where they are called the Aandenk Reef and the 'A' Facies respectively (Swart,1992). Swart (1992) states that the quartz pebble content (%) of the Reworked

BPM decreases to the north on Harmony gold mine, which suggests a north-south palaeocurrent direction.

Witpan Placer - At Harmony Gold Mine the Witpan placer consists mainly of massive conglomerates interbedded with minor matrix-supported conglomerate, trough cross-bedded arenite and fine grained argillaceous quartzite to siltstone. It is a channelized unit similar to the Reworked BPM. The Witpan placer is taken to be the base of the "A"-Reef at Western Holdings Mine. Blamey (1991) recognises three distinct components in the Witpan placer at Western Holdings (Fig.23). These are :

i) The basal scour unit - This is an oligomictic, grey, siliceous pebbly quartzite, with bimodal medium and large pebbles, with or without intercalated placer quartzites. Occasional angular ,yellow shale fragments are preserved. The basal scour unit has an erosional contact with the underlying Immediate Footwall Sequence. This unit attains a thickness of up to 1.2m.

ii) The reef zone - This is an oligomictic, medium-pebble, matrix-supported conglomerate that overlies the basal scour unit or the Immediate Footwall Sequence.The unit is crudely coarsening-upward. The average thickness of this unit is 120cm.

iii) Pyritic zone - This zone is pyrite-rich and is 10-25 cm thick. It is a pebbly pyritic-quartzite with medium to small, oligomictic pebbles set in a matrix of 50-90% pyrite with lesser amounts of quartz grains and very small subangular to angular clasts. This pyritic zone has also been recognised on President Steyn Mine. Carbon seams commonly occur on top of the zone and occasionally at the base. This has resulted in exceptionally good gold values with stope values varying from 10-65 g/t (Blamey,1991).

Uitsig Placer - The Uitsig placer is very similar at Harmony and Western Holdings gold mines, where it occurs as a sheet-like unit sitting on a scour surface. The placer reaches a maximum thickness of 40 to 60 centimetres at Western Holdings and Harmony mines respectively. Blamey (1991) includes the overlying light-grey , medium grained quartzarenite with the lower conglomeratic unit to form the Uitsig placer at Western Holdings. This quartzite contains scattered to sparse, fine dark chert fragments and is capped by shale in places on Western Holdings.This differs with the immature yellowish grey Uitsig hangingwall quartzite at Harmony. At Western Holdings the conglomerate is an oligomictic, matrix-supported, small pebble conglomerate that contains 1-20% pyrite in the matrix, with the pebbles at Harmony being described as medium. On President Steyn Mine, the Uitsig Reef has a carbonaceous facies which is significant in terms of gold tenor. Flyspeck carbon occurs on the lower contact as well as within the matrix of the reef (Blamey,1991).

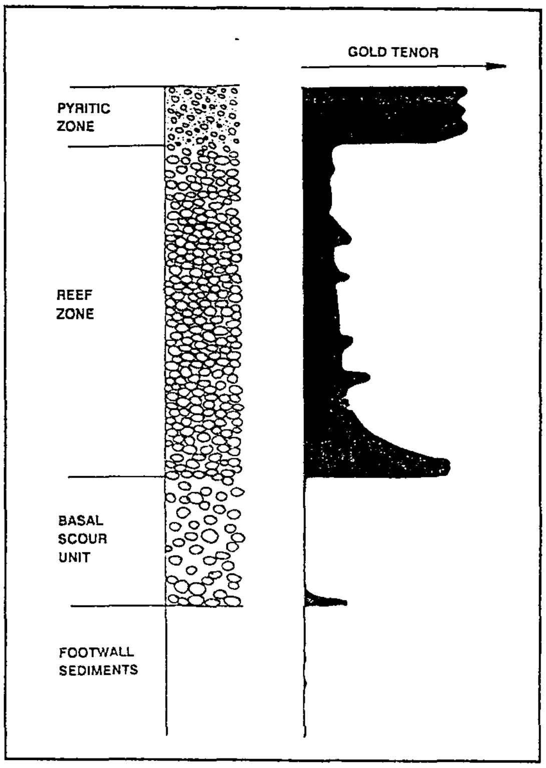


Figure 23 *Idealised section through the Witpan Reef at Western Holdings GM showing the typical positions of gold enrichment (After Blamey,1991).*

Hangingwall Grit - Swart (1992) describes the Hangingwall Grit granule conglomerate at Harmony Gold Mine as consisting of polymictic grits and SPC's, set in a light grey, mature, pyritic quartzite. It is separated from the Uitsig placer by an immature yellowish grey quartzite. The "HW Grit" unit generally scours into the underlying formations and has been seen to be in contact with the Reworked BPM. The bottom contact of the "HW Grit" is marked by an unconformity. A trough cross-bedded SPC with a pyritic matrix is associated with this contact.

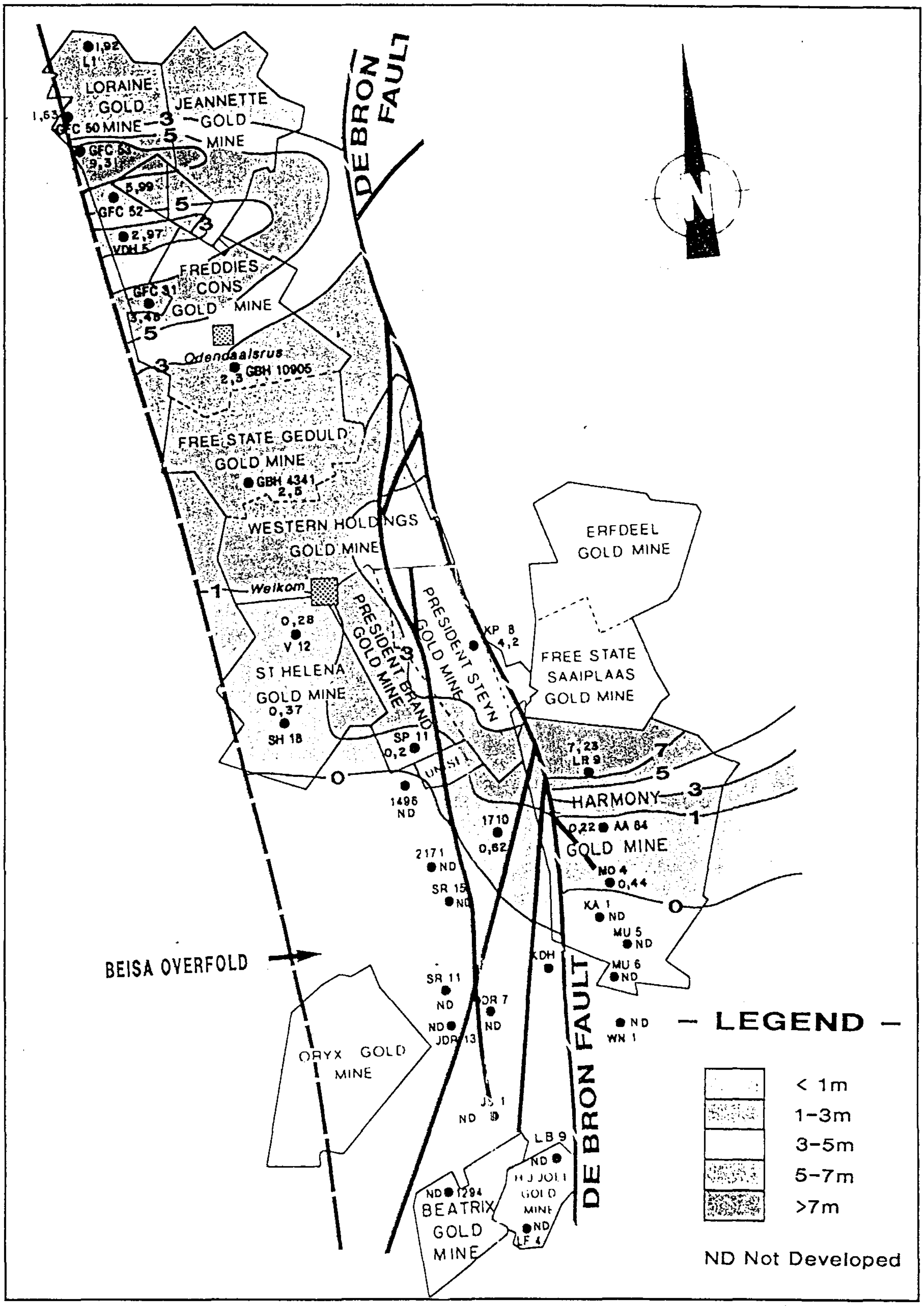


Figure 24 *Isopach for the A Reef Zone (after van Biljon ,in Ellis,1991).*

Upper "A" Placer - At Harmony Gold Mine this occurs approximately 3 to 5 metres above the Uitsig placer, and is a thin oligomictic massive to matrix supported small to medium pebble conglomerate. It is often pyritic, contains the largest percentage of chert pebbles relative to the other oligomictic "A" Reef placers and is capped by a black ripple-laminated shale. The upper "A" is truncated towards the south and east of Harmony Gold Mine by the Eldorado Formation. The zone containing this reef is known as the Earl's Court Reef Zone on Loraine Gold Mine (Jordaan, *in* Ellis *et al.*, 1991).

6.2 Directional Structures

6.2.1 Reef Thickness

As can be seen from the "A" Reef zone isopachs (Fig.24) the "A" Reef zone reaches a maximum thickness of over 9 metres and 7 metres at Loraine and Harmony Gold Mines respectively. Towards the south and south-west the package becomes progressively thinner with fewer internal quartzites being developed. Furthermore there is a marginal decrease in the size of the pebbles and the conglomerates become more clast supported and more oligomictic, indicating that some reworking has occurred in the distal areas of the braidplain. The "A" Reef

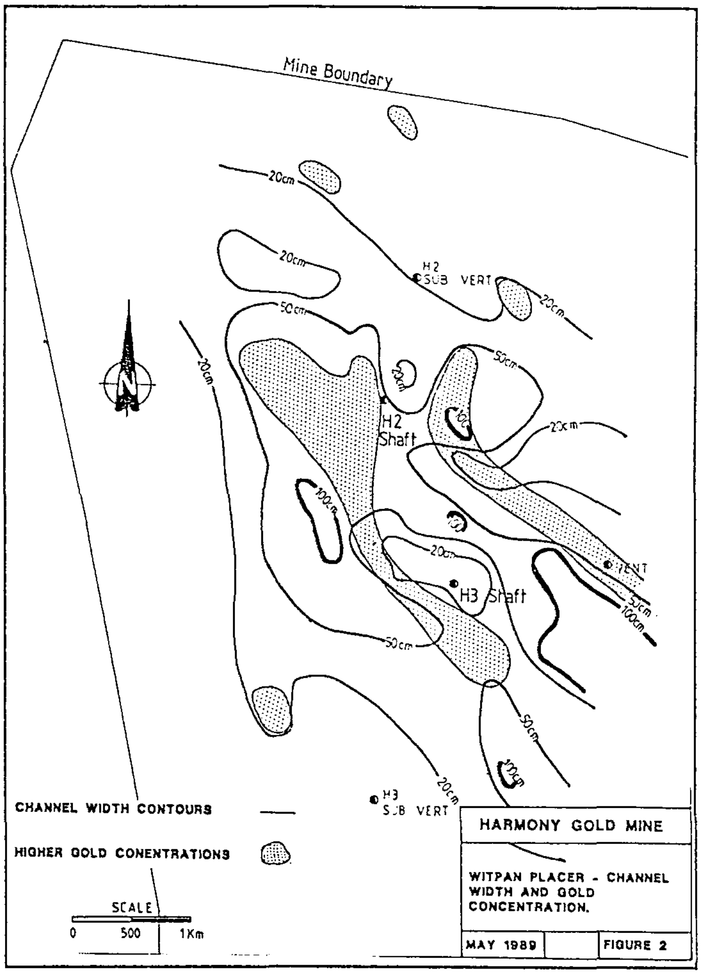


Figure 25 *Channel thickness and gold concentration patterns for the Witpan placer at Harmony Gold Mine (after Davies and Hatherly,1989).*

is truncated by the VS5 on the southern boundary of St. Helena Gold Mine and in the Merriespruit section of Harmony Gold Mine. The absence of the A Reef to the south of this is probably a combination of a decline in the energy level during deposition of the A Reef, in what is perceived to be a distal environment, and the scouring effect of the VS5 Reef (Van Biljon, *in* Ellis *et al.*,1991).

At Harmony Gold Mine, Davies and Hatherly (1989) modelled the Witpan and Uitsig placers in the area being mined (around H2 and H3 shafts) to identify channel thickness and gold concentration patterns. The Witpan placer shows a north-west to south-east trend for the channel thickness contours (Fig.25). This is corroborated by the channel thickness data from Western Holdings Mine shown in figure 26. Figure 27 shows the channel thickness and gold concentration pattern of the Uitsig placer at Harmony mine. The channel thickness contours exhibit a north-north-east to south-south-west trend which is almost perpendicular to that of the Witpan placer.

6.2.2 Palaeocurrent Direction

At the No.1 and No.2 Shafts at President Steyn Gold Mine Grobler (1989) states that the palaeocurrent direction is north-west to south-east for the Witpan and the Uitsig placers. At Harmony Gold Mine cross-bedding is generally absent in the massive conglomerates of the Reworked BPM, Witpan and Uitsig placers (Swart,1992). Trough cross-bedded conglomerates and arenites are abundant in the "HW Grit" granule conglomerate, which overlies the Uitsig placer. Measurements taken by Swart (1992) were plotted on a rose diagram (Fig 28) which shows a unimodal southerly palaeocurrent direction. The trough cross-bedded conglomerates show megatroughs (dunes) 1-2m wide and several metres long.

At Harmony Gold Mine Channel and scouring features are very common, especially in the Reworked BPM. Measurements are

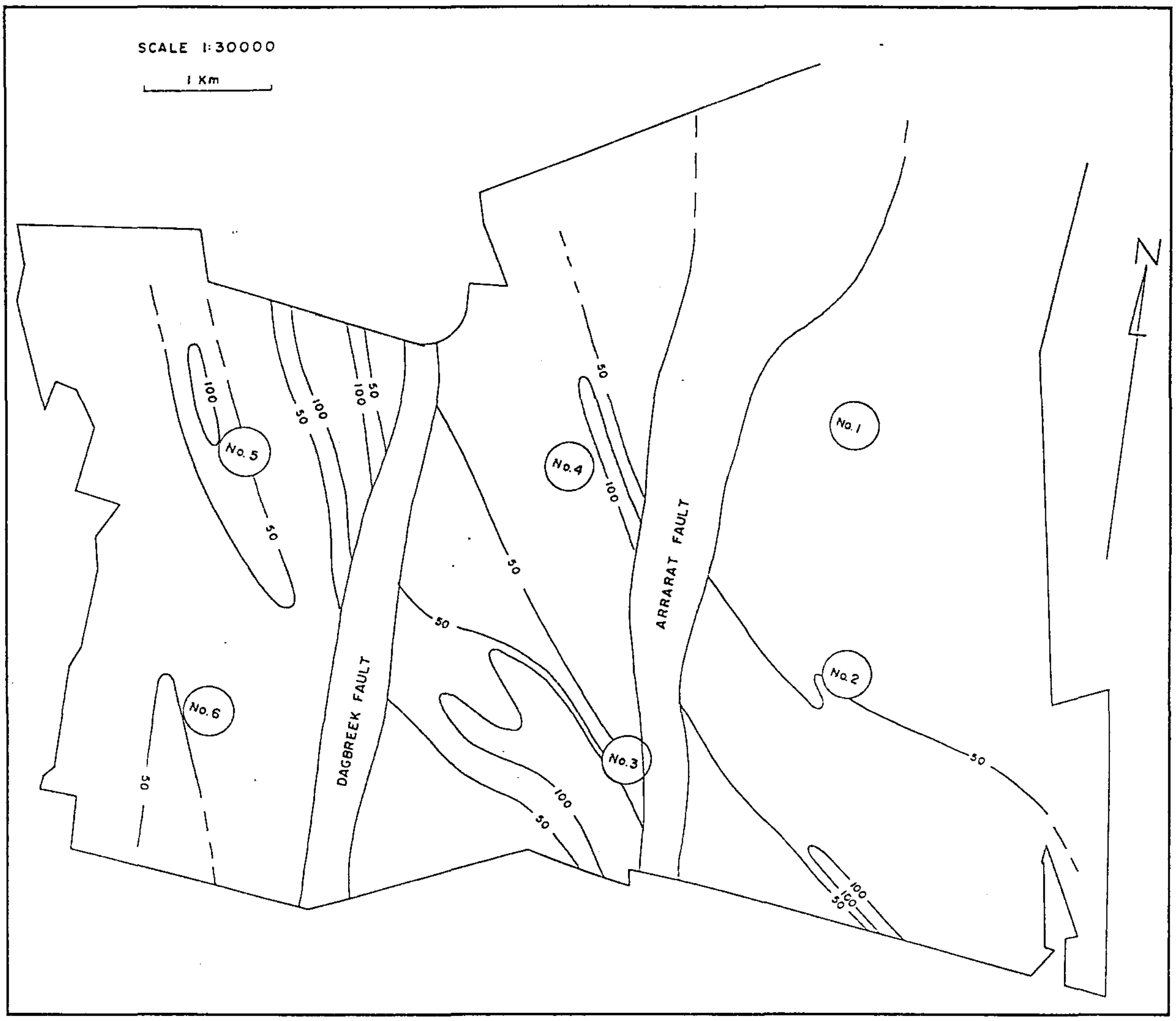


Figure 26 *Map of channel thickness (in cm), interpreted from borehole data, for the Witpan Reef on Western Holdings Mine(after Blamey,1991).*

summarised as vectors in the rose diagram in Fig.29. A strong bimodal orientation is indicated at right angles to each other. The south-west to north-east trend agrees with the thickness trends. The north-west to south-east trend is the same direction as the viable to marginal 'A' Reef areas at Harmony Gold Mine (Swart,1992) and channel-edge measurements and isopach maps for the Witpan Reef on Western Holdings (Fig.26).

6.3 Gold and Uranium Mineralization

During studies of the various placers in the "A" Reef zone at

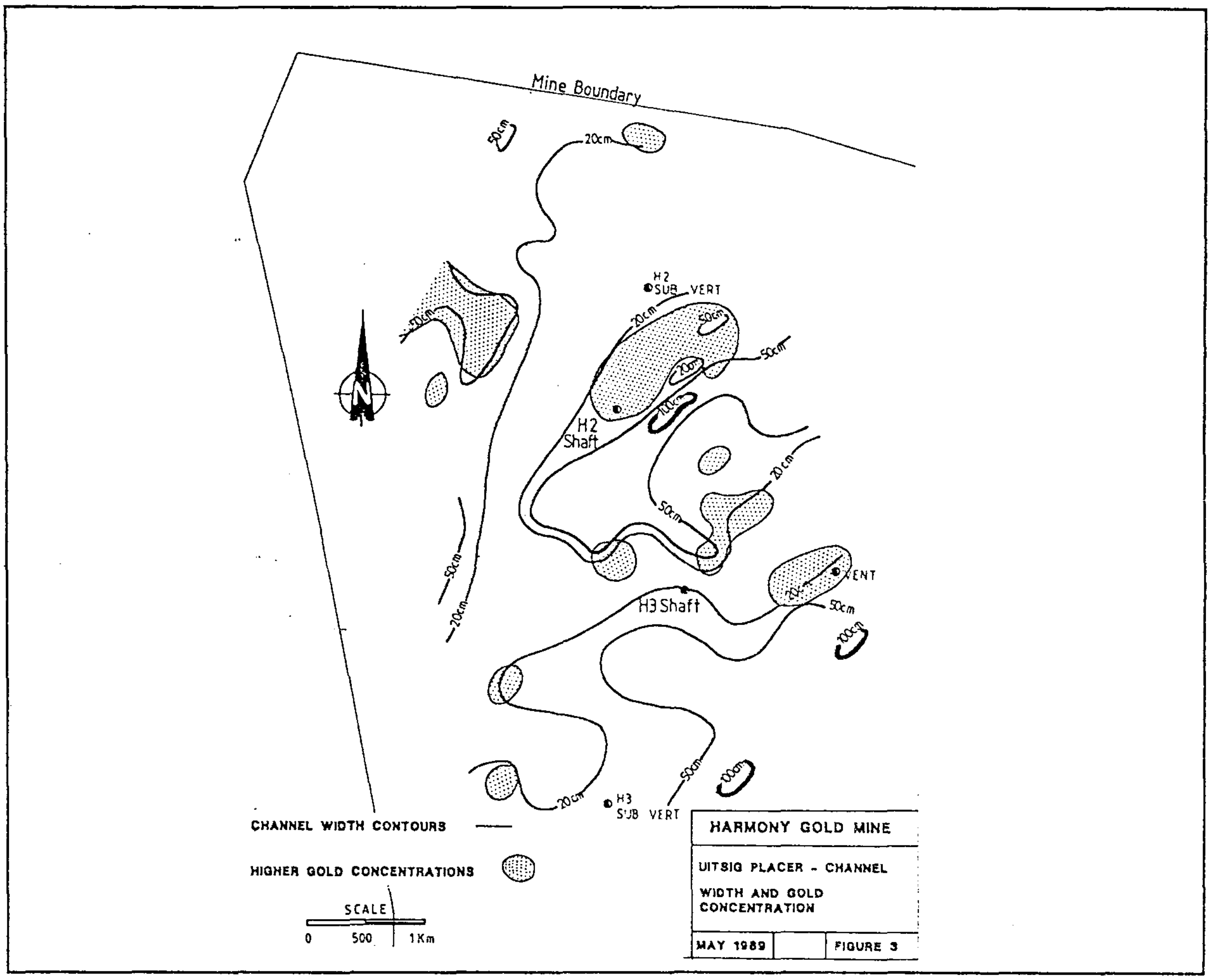


Figure 27 *Channel thickness and gold concentration patterns for the Uitsig placer at Harmony Gold Mine (after Davies and Hatherly, 1989).*

Harmony Gold Mine and Western Holdings Gold Mine by Swart (1992), Davies and Hatherly (1989) and Blamey (1991), several sedimentological features were found to be associated with the more highly mineralised areas.

Reef thickness - Swart (1992) states that in the Harmony No. 2 Shaft area the higher gold values in the Lower "A" Reef (Reworked BPM+Witpan) are generally associated with thicker reef areas and that the low value, thin reef areas represent palaeo highs.

Subenvironment - Swart (1991) found an enrichment in gold at channel edges for the Reworked BPM at Harmony Gold Mine. Davies

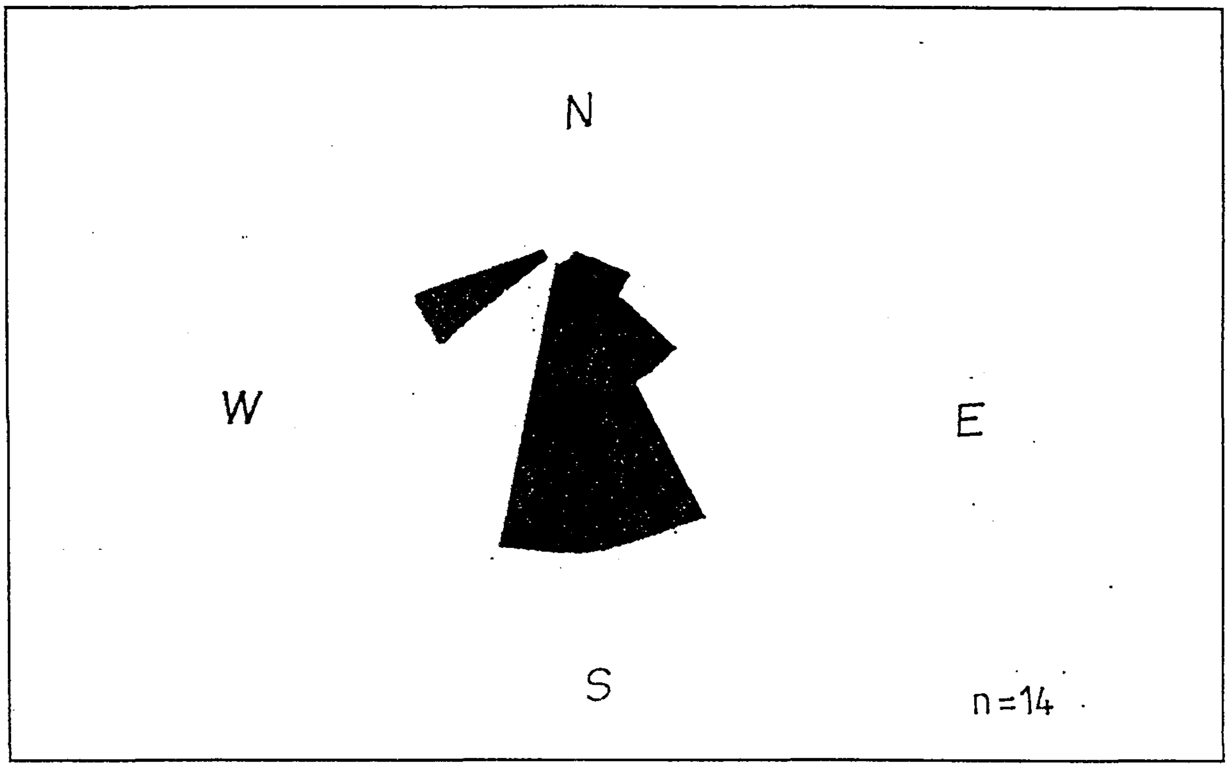


Figure 28 *"HW" Grit palaeocurrents at Harmony Gold Mine(after Swart,1992).*

and Hatherly (1989) describe an enrichment in gold in the deeper channel areas (50-100cm thick) and also like Blamey (1991) at Western Holdings Gold Mine at channel edges (20-50cm).

Stratigraphic position - In a sampling exercise Swart (1992) found that the highest gold and uranium values in the Reworked BPM occur at the top, near the Witpan interface with the lowest values generally in the middle. In the Witpan placer the gold and uranium values are highest at the base, and decrease gradually upwards by about 30%. In the Witpan reef at Western Holdings mine Blamey (1991) states that the most common sites for gold are the degradation surfaces within the reef horizon . Thus the contact of the basal scour unit which is generally poor in gold shows gold enrichment. The basal scour unit is generally poor in gold. The base of the "reef" zone is the next enriched zone. Within the "reef" zone the enriched zones are thought by Blamey (1991) to represent degradation surfaces. The pyritic zone at the top of the "reef zone" is also enriched in gold with

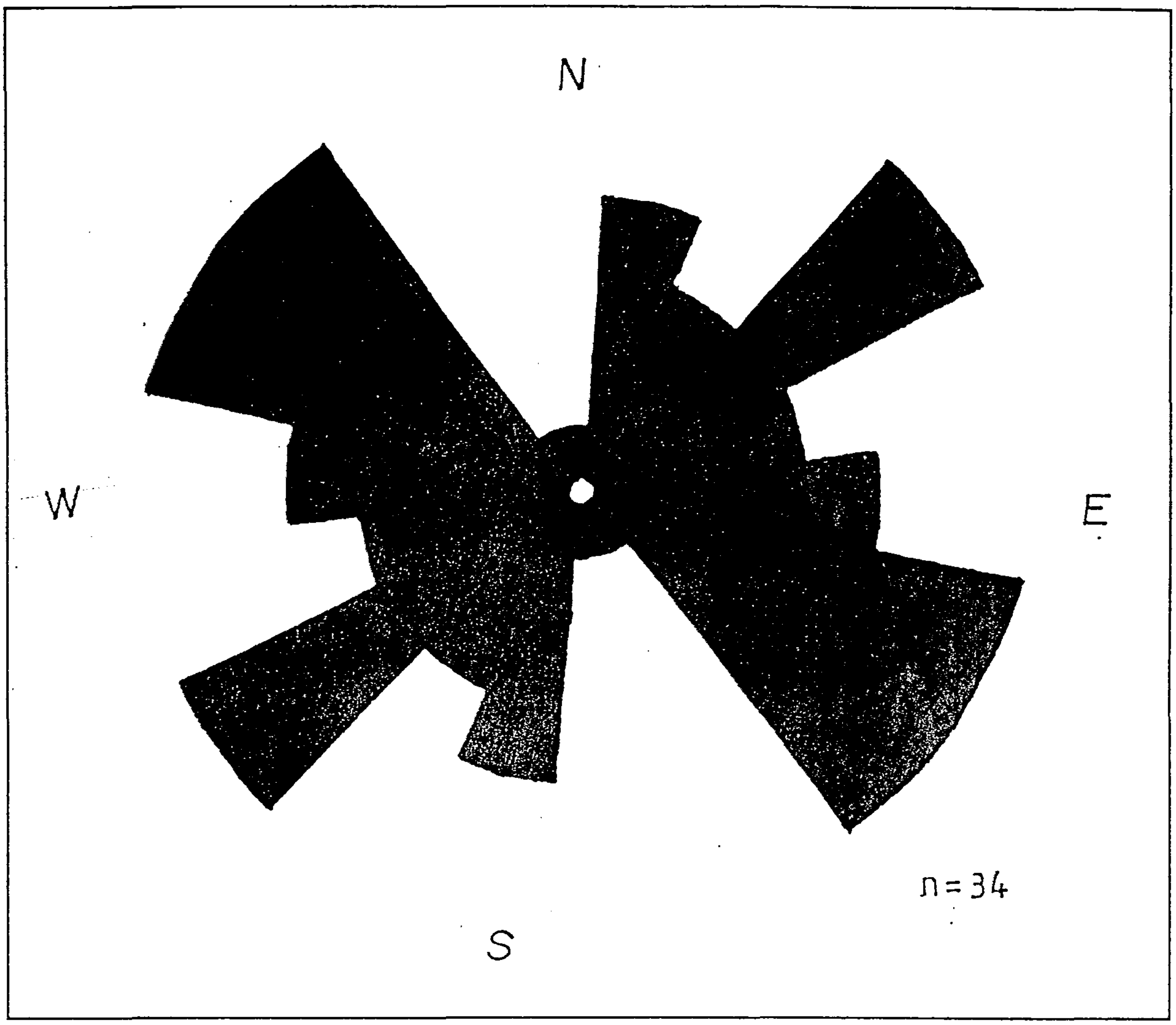


Figure 29 *Channel edge and scouring vectors for the Witpan and Reworked BPM placers (after Swart,1992).*

values of 5-20 g/t occurring over the entire pyritic zone. In the few areas that the Uitsig placer was sampled at Western Holdings the values did not show any particular tendency.

Carbon - Although the Uitsig reef is generally not mined at Western Holdings and Harmony mines, Blamey (1991) states that a carbon-bearing Uitsig reef occurs at President Steyn mine where gold values of 1000 to 1500 cmg/t over a channel thickness of 5-20cm are the norm.

Pebble sphericity - Blamey (1991) has indicated an increase in pyrite mineralization and gold tenor associated with pebble sphericity in the Witpan Reef at three localities at Western Holdings Mine.

Swart (1992) shows that pebble sizes bear no relationship to the gold and uranium values for the various A reef placers at Harmony mine. Davies and Hatherly (1989) state that at Harmony mine areas of higher gold concentration in the Witpan tend to be 200m to 300m wide and orientated north-west to south-east (Fig. 25). In figure 27 however,it can be seen that areas of higher gold concentration in the Uitsig placer are irregularly distributed but tend to lie on a north-west to south-east line, perpendicular to the contours of the Witpan placer.

7. The Beatrix Reef

7.1 Introduction

Johnston (1989) has described the sedimentary facies at the base of the Eldorado formation in the western margin of the Welkom Goldfield, where it overlies the Harmony and Dagbreek formations with an angular unconformity. These underlying formations were mainly lithified during the erosion of the Eldorado palaeosurface as indicated by the occurrences of small cobbles and occasional boulders of Dagbreek litharenites incorporated within the Eldorado formation. A moderate amount of palaeosol formation, mainly over the Dagbreek, was also present, indicated by steep scour surfaces.

Minter *et al.*(1988) believe that in the more distal reaches of the Eldorado fan, where transport power was insufficient to move coarse gravel and where muddy sediments accumulated, the pediment of the fan is composed of an alluvial veneer of disaggregated, eroded bedrock detritus resting on the palaeosurface. This detritus does not contain the polymictic clastic assemblage that is characteristic of the Eldorado Formation sediments and is unlike the light brown-coloured quartz-wacke of the Aandenk Formation below.

7.2 The Eldorado Pediment

The first record of placer sediment existing on the Eldorado palaeosurface was when Baines (1949), referred to an "uncorrelated reef" in a borehole (VDH1) north of Odendaalsrus. Feringa (1954) identified two conglomerates overlying the unconformity at the base of the Eldorado Formation in the G.F. Block. The lower oligomictic conglomerate he termed the Gold Estates Leader and the upper polymictic conglomerate the "Elsburg Basal Grit". Winter (1957) was able to identify the same two conglomerates in several borehole intersections in the Merriespruit section of Harmony Gold Mine. This placer is known as the Border Reef at Free State Geduld Gold Mine (Jordaan, in Ellis *et al.*,1991). Swart (1992) states that isolated values occur in this placer (known as the Eldorado Basal Conglomerate at Harmony Gold Mine) , but where it truncates the "A" Reef Zone, as in the south of Harmony Gold Mine, it becomes economically mineralised. Swart (1992) feels that the EBC can be correlated with the Beatrix Reef at Joel Gold Mine.

Johnstone (1989) states that the facies present at the base of the Eldorado range from planar-bedded, gritty litharenites (Sp) to highly-polymictic, poorly-sorted, debris flow conglomerates (Gmpl) to relatively oligomictic, moderately-sorted, large pebble/small cobble conglomerates (Gmol).

Descriptions of these basal Eldorado sediments have been provided by Minter *et al.*,(1988) and Johnstone (1989). The Eldorado pediment seems to consist of two main facies types. The first comprises thin, scour-based, conglomerate layers of large oligomictic pebbles (max diam =45mm) (Gmol) overlain by coarse-grained, trough crossbedded quartz arenite (or planar-bedded, gritty litharenites (Sp) in Johnstone's (1989) description) and then by thin shale partings. These sequences are repeated, representing multiple fluvial channel fill events. The second facies is a black diamictite. It occurs in multiple layers 1 to 5 cm thick and contains unsegregated oligomictic pebbles, mudflakes, and detrital pyrite. The layers grade into black shale laminae. These are considered by Minter *et al.*(1988) to represent mudflows from the Eldorado fan that have swept up eroded pebbly and heavy mineral detritus from the palaeosurface and incorporated intraclasts from desiccated, previously deposited muds.

From the descriptions of Minter *et al.*(1988) and Johnstone (1989), it seems that the vertical profiles demonstrate a complex association of the channel and bar sediments (Gmol and Sp), and intervening debris flow deposits (Gmpl). In his study area Johnstone (1989) states that the Gmol and Sp facies predominate in the vicinity of the Basal and Leader subcrops whereas to the east of this, in a palaeo depression, the Gmpl facies predominates. Collectively these facies thicken towards the palaeo depression.

7.3 Nature of the Beatrix Reef

The Beatrix Reef (at Beatrix Gold Mine) is taken to be the conglomerate and the interbedded arenite deposited on the unconformity surface overlying the Virginia Formation (Genis,1990). The upper contact of the Reef is taken as the scour surface at the base of the first dark-grey lithic arenite/wacke, or at the base of the first black argillite parting. As such the Beatrix Reef zone, in the definition used on the mine, incorporates the conglomeratic remnants of the Aandenk Formation which occur in the northeastern part of the mine (the "A" facies), the Beatrix Reef per se, and the V.S.5 conglomerate which is sporadically developed at the base of the Eldorado Formation. The 'A' Facies comprises oligomictic conglomerate layers in a yellow-grey quartz-wacke matrix. The yellow-grey "argillaceous quartzite" matrix and interbeds are similar in character to typical Aandenk Formation sediments.

The Beatrix "facies" at Beatrix Gold Mine has been divided by Genis (1990) into three subfacies. These are:

The oligomictic conglomerate facies - This facies consists of small to medium oligomictic quartz pebble conglomerates with a grey quartz arenite matrix and can probably be correlated with the Gmol facies described by Minter *et al.*(1988) and Johnstone (1989) on the Eldorado pediment. This facies is seen to occur throughout the mine. There seems to be a gradational variation between clast supported and matrix supported end members. The conglomerate is oligomictic, consisting of 98% white or smoky vein quartz. The clasts are moderate to well rounded and generally of prolate or spheroid shape. The matrix consists of varying proportions of quartz arenite and heavy mineral grains such as pyrite (the matrix can consist of up to 85% pyrite). Cross-bedded quartz arenites are commonly interbedded with the conglomerate, particularly in the thicker reefs.

The trough cross-bedded pebbly arenite facies - Where the arenite matrix increases and the conglomerate becomes more matrix supported, cross-bedding becomes more prevalent. The dominant structure is large-scale trough cross-bedding in sets of about 15cm thick. The foresets are usually marked by varying concentrations of detrital pyrite. This facies probably corresponds to the coarse-grained, trough cross-bedded quartz arenite mentioned by Minter *et al.*(1988).

The planar cross-bedded pebbly arenite facies - This facies is not as common as the trough cross-bedded facies. It is observed in pebbly quartz arenites. The cross-bed sets are either 5cm or 8-10cm thick. Reactivation surfaces are common. This facies probably corresponds to the planar-bedded, gritty litharenites (Sp) facies mentioned by Johnstone (1989).

The VS5 facies comprises polymictic small pebble conglomerates with a dark grey, lithic-wacke matrix.

Isopachs illustrating thickness variations of the Beatrix Reef (Fig.30) and trends of erosional scours into the footwall lithologies define a generally north-south to north-west south-east braided pattern of channels etched into the Eldorado palaeosurface (Fig.31).

Palaeocurrent indicators suggest a transport direction towards the south-south-west. This is supported by a decrease in the average largest clast size from 25mm in the north to less than 20mm in the south of Beatrix (Fig.32).

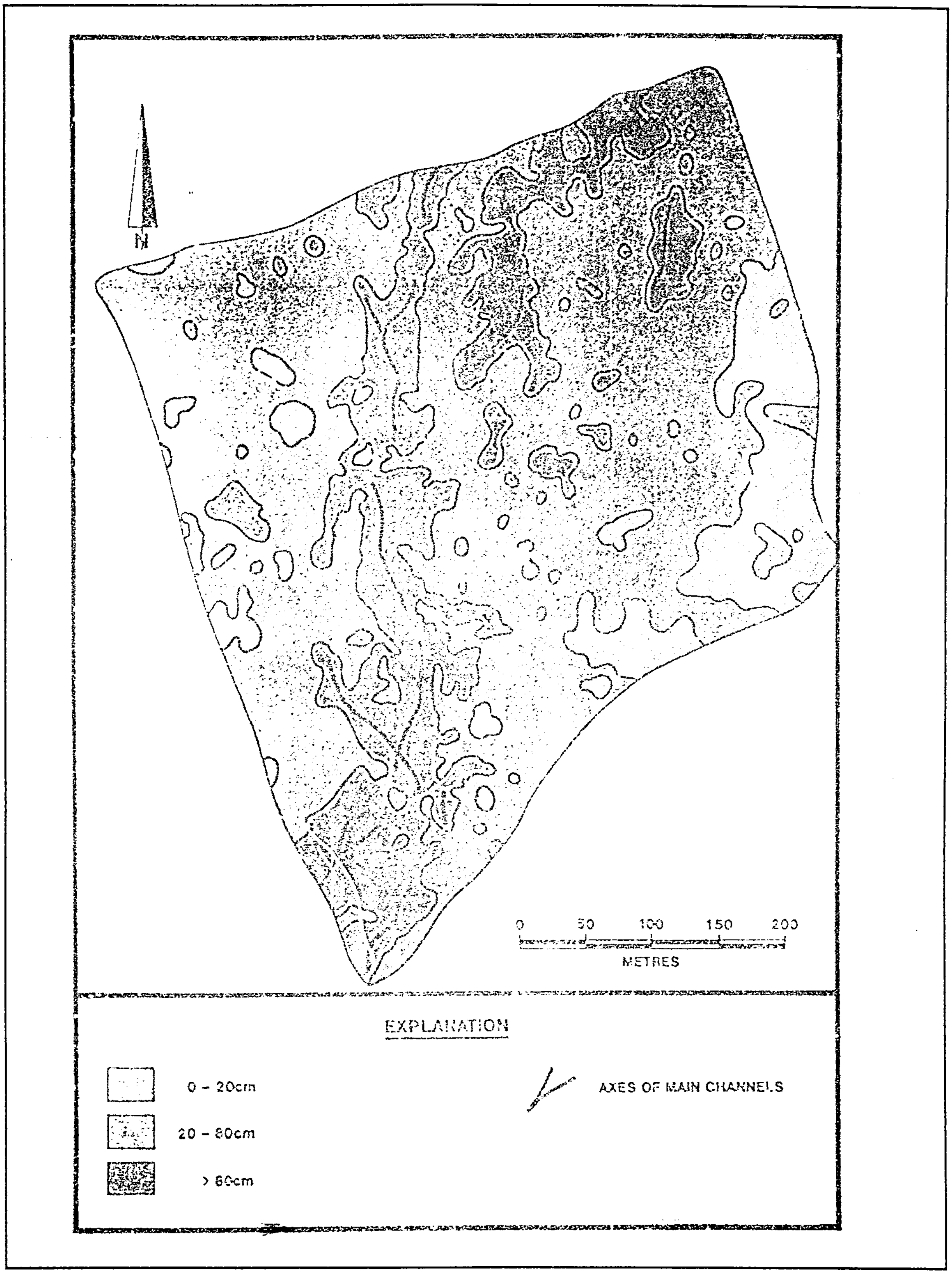


Figure 30 *Beatrix Reef isopachs of reef thickness at Beatrix Gold Mine (after Genis,1990)*

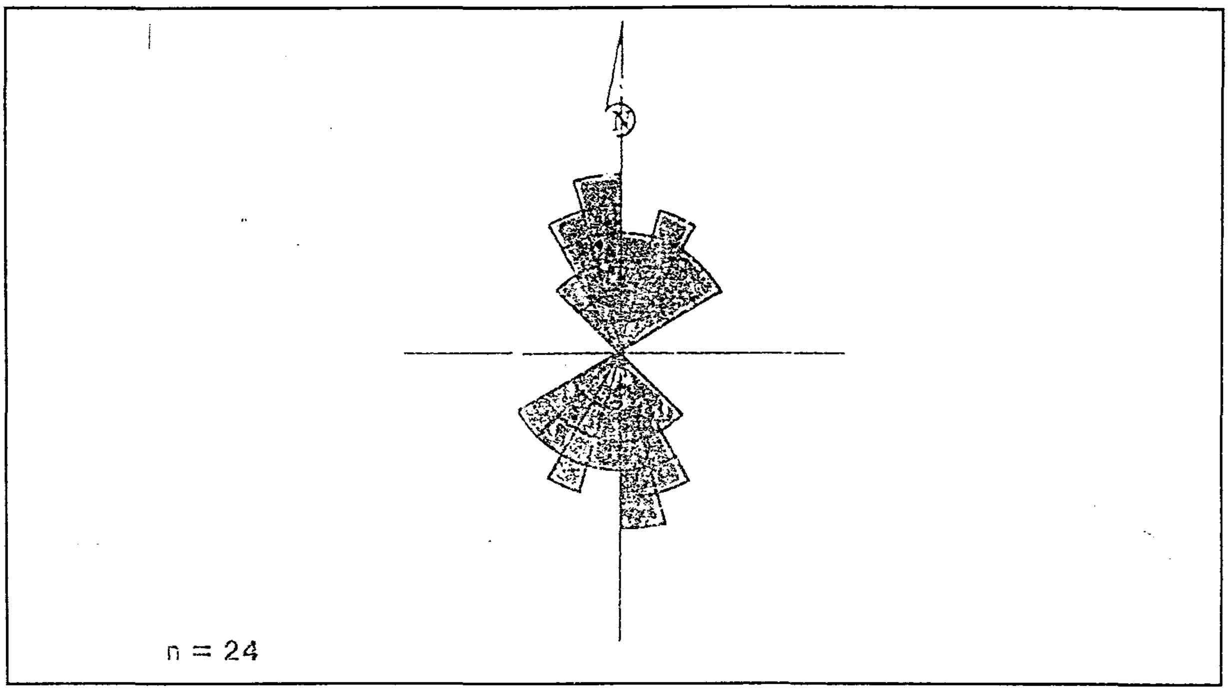


Figure 31 *Rose Diagram of the orientation of Beatrix Reef channel scours (after Genis,1990).*

7.4 Mineralization

7.4.1 Heavy minerals

Pyrite is the most common heavy mineral present in the Beatrix Reef, comprising over 85% of the heavy mineral suite (Genis,1990). Other minerals include chromite, ilmenite, leucoxene, zircon, uraninite and brannerite, galena and other Fe and Cu sulphides. Minter *et. al.*,(1988) cite the lack of uraninite in favour of brannerite as indicating that the heavy mineral suite in the Beatrix Reef was derived from older placers with the alteration of the uraninite to brannerite during the weathering of the older placers.

Minter *et al.* (1988) regard the placer minerals found in the Beatrix Reef as having been released during disaggregation of stratigraphically lower placers during erosion and reworking. They state that the suite of ore minerals identified in the

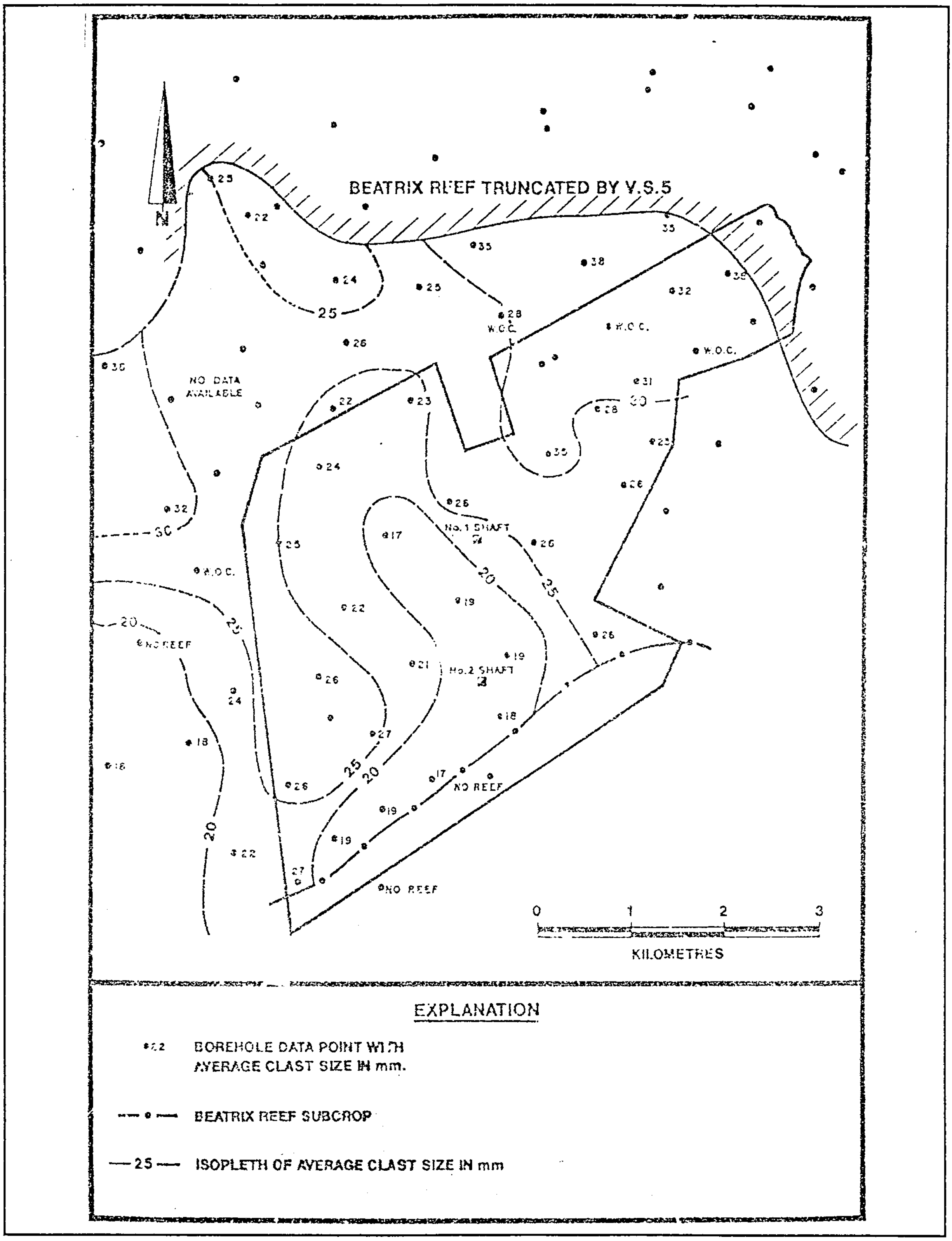


Figure 32 *Average largest clast size in Beatrix Reef in surface boreholes (after Genis,1990).*

placer alluvium on the Eldorado pediment resembles that present in subcropping placers. This indicates that either the source of supply of placer minerals did not change, or that outcrops of the underlying placers provided a local source during erosional processes. The presence of fragmental and apparently abraded pyrite, of a form normally found as secondary authigenic pyrite in Witwatersrand ores, indicates that it may have been derived by the erosion of older outcropping placers. Minter *et al.*(1988) state that this possibility is supported by the granular nature of the kerogen present in the placer alluvium and by the fact that uraninite usually found enclosed in the kerogen has been altered to brannerite. At Beatrix Gold Mine, Genis (1990) found a high content of uraninite and brannerite (10% of the heavy mineral suite) with brannerite occurring more frequently than uraninite and commonly as an alteration product of uraninite. Genis (1990) proposes that irregular altered encrustations of brannerite could also be uraniferous leucoxene. Minter *et al.* (1988) state that the alteration of uraninite to brannerite, by reaction of uranium-bearing solutions derived from uraninite with allogenic titanium-bearing minerals (titanomagnetite, ilmenite, etc.), has been described by many investigators of the Witwatersrand placers. The reaction requires oxidation, and in the absence of any other evidence for oxidation, it is assumed that some oxygen was present in the atmosphere over the palaeosol.

7.4.2 Gold

Carbon is fairly common in the conglomerates of the Beatrix Reef. It occurs as "flyspeck" carbon on the basal parts of lag conglomerates. In-situ carbon seams are sometimes observed (up to 5mm thick) on the unconformity surface at the base of the reef. Thin carbon seams also occur on scour surfaces within the reef, and on unconformity surfaces at the base of the Rosedale Member. Increased gold concentration occurs in areas of carbon accumulation such as in the lag conglomerates and carbon seams. The carbon in the seams is columnar and fine films or dustings of gold are occasionaly visible between the columns.

The other two main facies, Sp and Gmpl, contain moderate to low amounts of ore minerals respectively. Both Johnstone (1988) and Genis (1990) describe the concentration of gold with pyrite grains in thin accumulations on bedding surfaces such as foresets. Genis (1990) also states that gold is preferentially concentrated along the top of the reef. Johnstone (1988) states that ore minerals are strongly associated with the Gmol facies while gold is mainly associated with upper contacts and, to a lesser degree, lower contacts.

Minter *et al.* (1988) observed a relationship whereby the detrital pyrite and gold is concentrated in the clast-supported layers and on scour surfaces of the Gmol facies. From autoradiographs they were also able to determine that uranium mineralization is also concentrated at these sites, indicating that it is associated with the bed-load heavy mineral concentrates.

Genis (1990) states that an enhanced concentration of gold occurs along unconformities in association with lag conglomerates, and in areas adjacent to the thickest reef development, i.e. along the flanks of channels.

Genis (1990) states that detailed sedimentological mapping does not show broader scale lateral variations associated with larger scale sedimentary features such as channels or bars. In the detailed study that he undertook at Beatrix Gold Mine, Genis (1990) found a correlation between high gold concentrations and areas of reef less than 20cm thick and as linear zones along channels.

7.5 Model of sedimentation

Remnants of the Aandenk Formation unconformably overlying the Virginia Formation are preserved below the unconformity at the base of the Beatrix Reef in the northern parts of Beatrix Mine

(Genis 1990). The extent of the unconformity surface and the degree of truncation of the underlying strata suggests that tectonic uplift was the cause of this base level change. A change in eustatic sea level generally does not take place over a range sufficiently large as that required to cause such an angular discordance. Genis (1990) therefore does not believe that the base level change was due to a marine transgression. The angle of the disconformity increases in a westerly and southwesterly direction, as does the degree of truncation of the footwall beds. This suggests uplift and the basin margin to the west.

8.Genesis of Gold Mineralization

Skinner and Merewether (1986) have classified the theories concerning the origin of the gold in the Witwatersrand basin into three main groups. These are:

1) The deposit is a palaeoplacer and the gold and other heavy minerals had been washed into the basin by fluvial agencies and had settled out together with the sand and the pebbles. The classic placerist school has converted to the modified-placer theory, to account for the crystalline, not water-worn, habit of the gold particles, the variety and paragenesis of the several sulphides in the matrices of the reefs, and the relation between uraninite and carbonaceous matter. Metamorphosis was ascribed to thermal fluids of unknown origin, which dissolved the detrital constituents and reprecitated them virtually in situ.

2) The deposit is syngenetic and the gold was introduced by precipitation from a solute complex in surface waters.

3) The deposit is epigenetic and the gold was introduced by hydrothermal solutions that ascended through the porous, clastic sediments.

Pretorius (1989,p9) states that the epigeneticists are divided into two camps over the source of the hydrothermal fluids. Certain supporters held to the idea that the fluids were of magmatic origin and had been a product of either Ventersdorp or Bushveld igneous activity. Another group favoured the fluids as having been derived from metamorphic dehydration of the substantial volumes of argillites in the lower part of the Witwatersrand stratigraphic succession.

Table I and II present the main arguments that have been used in the past against the placer and hydrothermal origins of Witwatersrand mineralization respectively.

Table I

MAIN ARGUMENTS ADVANCED AGAINST PLACER ORIGIN OF WITWATERSRAND MINERALIZATION (after Pretorius 1989)

- Δ no adequate source established for extraordinary volume of gold
- Δ absence of unequivocal nuggets of gold
- Δ very small particle-size of gold atypical of recent placers
- Δ secondary crystalline and hackly habit of gold particles
- Δ low fineness of gold atypical of recent placers
- Δ association of gold with wide variety of secondary sulfides
- Δ gold in two end-member chemical associations (Au-Fe-S-As and Au-C) typical of epigenetic mineralization
- Δ absence of 'black sands' (magnetite, ilmenite, hematite) characteristic of recent placers
- Δ abundance of idiomorphic pyrite
- Δ 'detrital' pyrite and uraninite unlikely to have survived oxidizing environment and fluvial transportation

A further fundamental division in theories on the source and genesis of the gold centred on whether the metal had had an exogeneous or an endogenous origin. Most investigators, hydrothermalists or placerists, saw the fluids or the detrital particles as having been derived from a source-terrane outside the limits of the basin, but some geologists, again of both schools, put forward that the primary gold mineralization had been sited in the Dominion and West Rand groups of the Witwatersrand Sequence, from which formations it had been mechanically or metamorphically reworked into the Central Rand Group during a terminal, regressive, sedimentological phase in the depository's history.

Pretorius (1989) summarised four new models that were produced at the Centenary commemoration in 1986 and these are shown in tables III,IV and V.

Table II

MAIN ARGUMENTS ADVANCED AGAINST HYDROTHERMAL ORIGIN OF WITWATERSRAND MINERALIZATION (after Pretorius,1989).

- Δ no evidence of channelways along which hydrothermal fluids moved
- Δ absence of mineralogical zoning typical of hydrothermal deposits
- Δ juxtaposed high-gold-content and virtually-barren conglomerates of essentially identical composition
- Δ equal intensity of gold mineralization in 'low-permeability' pyritic quartzites and nearby 'high-permeability' conglomerates
- Δ isolated blocks of well-mineralized conglomerate floating in barren, relatively-impermeable diamictites
- Δ high spatial correlation between gold, uraninite, and unequivocally-detrital zircon
- Δ intimate relation between heavy-mineral localization and sedimentary structures
- Δ rich concentrations of gold, without pebbles, pyrite, uraninite, kerogen, on parting-planes/unconformities
- Δ zircon, chromite, leucoxene, some uraninite, some pyrite in hydraulic equilibrium

Table III

SELECTED NEW CONCEPTS OF ORIGIN OF WITWATERSRAND GOLD

CENTENARY MODELS I AND II (after Pretorius, 1989).

syngenetic origin : Hallbauer (1982-1988); Robb (1986-1988)
gold, uraninite, sulfides, 'carbon' granules, derived from hydrothermally-altered (propylitized, sericitized) granites in hinterland to NW

epigenetic origin : Phillips (1986-1988)
gold, sulfur introduced into conglomerates by metamorphic aqueous fluids guided by faults, bedding-planes, unconformities, dykes; deposition of gold controlled by horizons rich in iron and kerogen; source of gold in metamorphic fluids not specified; ".... alternative genetic model to the placer (unmodified and modified) model is not offered ...."

Table IV

SELECTED NEW CONCEPTS OF ORIGIN OF WITWATERSRAND GOLD

CENTENARY MODEL III (after Pretorius,1989).

syngenetic origin : Hutchinson and Viljoen (1986-1988)

§ endogenous, rather than exogenous, source

§ leaching by heated sea-water of buried basalts of Dominion Group (base of WWR sequence)

§ silica, iron, gold in consequent hydrothermal fluids which vented on sea-floor along basin-margin faults

§ formation of proximal, pyritic, auriferous exhalites and distal, oxidic, ferruginous shale of West Rand Group (lower-middle of WWR sequence)

§ exhalites reworked on regressive basin-margin by fluvio-deltaic processes to form pyritic, auriferous conglomerates of Central Rand Group (top of WWR sequence)

§ Witwatersrand mineralization coeval with Archean greenstone lodes at 2600-2900 Ma

Table V

SELECTED NEW CONCEPTS OF ORIGIN OF WITWATERSRAND GOLD

CENTENARY MODEL IV (after Pretorius,1989).

syngenetic origin : Pretorius (1986-1988)

- § Witwatersrand = back-arc basin; magmatic arc to NW
- § age of Witwatersrand Sequence = Late Archean (2700-3000 Ma)
- § pronounced activity in magmatic arc at 2800 Ma pene-contemporaneous with deposition of Central Rand Group
- § rapid succession of : porphyry-type and epithermal gold mineralization in magmatic arc → almost coeval erosion and fluvial removal → episodic deposition of detrital gold in distal braid-plains and braid-deltas of Central Rand Group (host to 98% of WWR gold)
- § reconstitution of reefs by pervasive metamorphic fluids emanating from continued activation of magmatic arc, including Ventersdorp volcanism (2400-2700 Ma) and Bushveld Complex (2000-2100 Ma)
- § Witwatersrand : simply, the jewel in the Golden Crown of the Late Archean

9. Palaeoenvironmental Reconstruction

9.1 Introduction

Any model to try and reconstruct the Spes Bona/Aandenk palaeoenvironment needs to take the following sedimentological features into account:

1) The prominent disconformities
2) The very robust nature of the BPM
3) The presence of carbon in the "B" ,"A" and Beatrix Reefs
4) The SW/NE , NW/SE and N/S palaeocurrent directions for the "B", "A" and Beatrix Reefs respectively.
5) The maturity of the "A" and Beatrix Reefs.

9.2 Tectonics

With respect to the first two features, Callow and Myers (1986) state that marginal unconformities below the main placer deposits and increasing pebble size in successively higher reefs from the Basal Reef (Welkom Formation) to the Big Pebble Reef (Aandenk Formation),(Table VI) indicate that the basin margins were being uplifted and migrating towards the basin centre throughout this time. They state that diamictite deposition and increasing angularity of unconformities indicate that this early deformation reached its climax during or shortly after the

Table VI

PALAEOCURRENT AND PEBBLE SIZE MEASUREMENTS FROM THE WELKOM FAN, O.F.S. (after Sims,1969).

HORIZON	PEBBLE SIZE MM	PEBBLE SIZE Ø	MEAN PALEOCURRENT
ELDORADO QUARTZITE	-	-	106
BIG PEBBLE REEF	133.0	-7.1	96
B REEF	90.4	-6.4	
LEADER REEF	34.8	-5.1	0.70
LEADER CENTRAL*	32.0	-5.0	0.95
LEADER REEF*	30.0	-4.9	0.75
BASAL REEF	23.3	-4.5	010

deposition of the Eldorado sediments.

From the distribution of basin edge unconformities, it can be deduced that the Welkom fan depository was tectonically active on the western, southern and eastern margins during sedimentation. Callow and Myers (1986) however state that palaeocurrent studies indicate that sediment was transported predominantly from the south and west. Palaeocurrent directions derived from the Welkom fan show a distinct change from northerly during deposition of the in the Basal Reef to easterly during deposition of the Leader Reef (Table VI). This change is preceded by the deposition of the Harmony Formation diamictites. The easterly transport direction is present in the successive reefs above the Leader Reef. The western margin of the basin is defined by a steep monoclinal fold, locally overturned, with associated thrusts (Olivier, 1965). Along the western margin the basin edge unconformities are closely spaced and restricted largely to the steep portion of the monocline. This indicates that the fold structure was active during sedimentation and defined the western margin of the basin after the deposition of the Basal Reef. The southern and southeastern margins of the basin remained essentially passive during this time with only low angled unconformities indicating uplift along these margins.

Callow and Myers (1986) believe that many of the features in the Welkom Goldfield are evident in areas of the Rocky Mountain Foreland where large monoclinal folds with associated thrusting occur. These structures have been shown to form as a response to basement block faulting under compression.

Response to this style of deformation is characterised by the development of genetically related mountain belts and intermontane basins. These basins contain coarse clastic sediments and generally have several tectonically active margins.

9.3 The Spes Bona and Aandenk Formations

Callow and Myers (1986) therefore believe that the progressive development of the Welkom placers can be modelled in terms of relative motions on two major basement blocks and the consequent deformation of the relatively thin sedimentary cover.

The principal components in this model are a rising western block and a related, gently tilting eastern block. Following the deposition of the West Rand Group on a stable cratonic platform, the platform was tectonically disturbed and the coarse Johannesburg sediments were deposited. At the end of Basal Reef time a second major tectonic event disturbed the basin resulting in the Basal Reef-Leader Reef unconformity, the change in palaeocurrent directions, and the deposition of the Harmony Formation diamictites. Relative motion on the two basement blocks began at this time.

Post Leader Reef uplift on the western block resulted in the accentuation of the monoclinal structure. Associated northwestward tilting of the eastern block resulted in the development of intraformational unconformities along the passive southern and southeastern margins.

Myers *et al.*,(1990) state that evidence for the timing of the folding that caused the large overturned monocline which is developed along the entire length of the western margin of the goldfield is provided by associated changes in stratigraphic thickness within the Central Rand Group adjacent to this structure. The section from the Oryx Gold Mine in figure 33 portrays the progressive thinning of the entire Central Rand Group into the monoclinal structure which is an indication of progressive development of the monocline during sedimentation. The coarsening upward nature of the Central Rand Group is pronounced in this area with the uppermost sediments consisting of the boulder conglomerates of the Eldorado Formation.

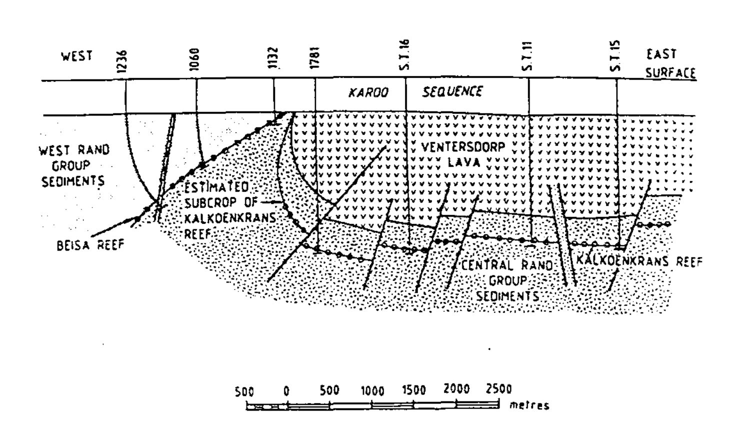


Figure 33 *Summary geological section across Oryx Gold Mine (after Star,1988 in Myers et al.,1989)*

Jordaan (1989) and Kingsley (1992) both subdivide the Spes Bona and Aandenk Formations into two distinctive facies associations, viz. alluvial fan and braided alluvial plain. The former is characterised by an immature sediment assemblage that was distributed as sheetwash deposits radially eastward. Jordaan (1989) believes that the six palaeoplacers in the Aandenk and Spes Bona Formations in the Welkom goldfield (the "B", The Reworked BPM (or Kimberley No.4 Reef), Lower, Middle and Upper "A" and the Beatrix Reef) were all deposited in a braided stream environment, the "B" reef in a transverse direction and the "A" Reefs in a longitudinal direction in the basin. Kingsley (1992) interprets the "B" Reef and other channel sediments as representing fanhead deposits and the "A" Reef braided alluvial plain deposits.

Drainage patterns show the presence of transverse alluvial fan and longitudinal braided stream drainage patterns (Fig. 34). Sediment was discharged through the fanhead trench, and redistributed by distributary channels on wet alluvial fans. The immature arenites were deposited mainly by sheetwash processes, during cyclical flooding events on featureless alluvial fan slopes. Regional gold distribution patterns suggest that juvenile gold was supplied by alluvial fans, and primary gold mineralization formed as a result of detrital concentration in braided streams.

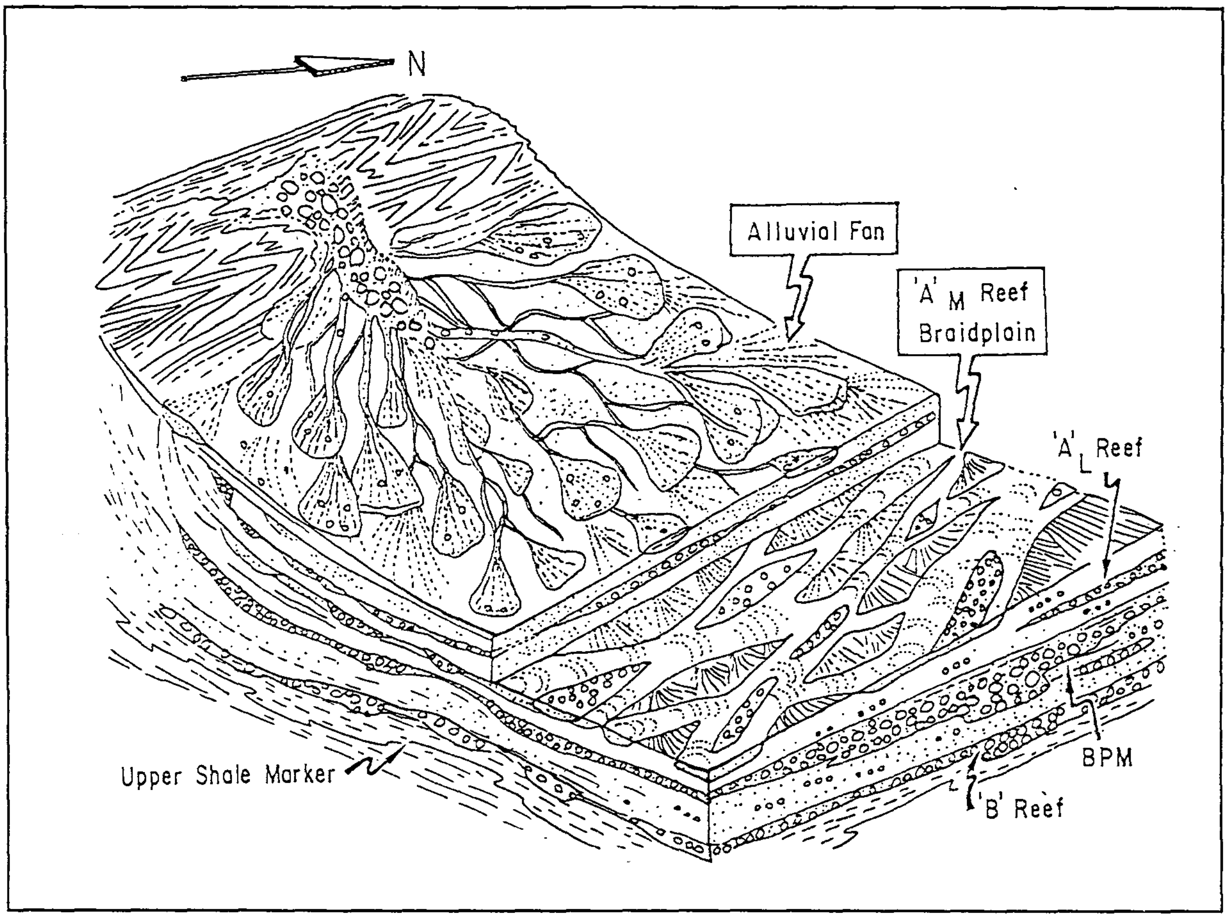


Figure 34 Block diagram showing the depositional environments and transport directions of the Spes Bona and Aandenk Formations in the O.F.S. Goldfields (after Jordaan, 1989).

Obstructions in the form of longitudinal drainage systems, which led to bar building and associated gold and uranium mineralization, are among the sedimentological controls which strongly point to mechanical processes in gold and uranium concentration.

Minter (1978,p805) suggests that the coarse gravel units within the Spes Bona member represent internal responses on the fan, caused by particular floods or an exceeding of the fan's geomorphic threshold. The B placer is confined to discrete interconnected channels. Transverse bars of avalanche -bedded pebbly sand and longitudinal bars of gravel developed within the channels and spread laterally. The placer channelways range in width from 1 to 200m and are up to 2m deep, but shallower in distal locations. Mapping of their edges indicates a sinuosity that meanders within an arc of 110 in a braided pattern that bifurcates and joins (Minter,1978). The channel sediments have not spread sufficiently to produce a sheet of sediment, but are confined to channelways. As a result of this confinement, the gold distribution follows a simple drainage pattern.

The B placer, which onlaps the Dagbreek Formation along the southern and western margin of the Welkom goldfield, has a dispersal pattern perpendicular to isopach contours of the truncated Dagbreek Formation in Figure 35 and is supported by discrete, entrenched channel directions and cross-bedding to the northeast (054°) at the northern end of the goldfield (Minter, 1978).

Victor (1989) did a statistical analysis on exploration drilling and reef drive sampling data at the Free State Saaiplaas Gold Mine 5 Shaft. This data showed that :

i) Mean gold concentration decreases exponentially with an increase in the orebody thickness.

ii) The gold tends to concentrate at the basal contact of the reef.

iii) The higher gold concentrations are associated with deposition ofthe B Reef conglomerate on footwall shale.

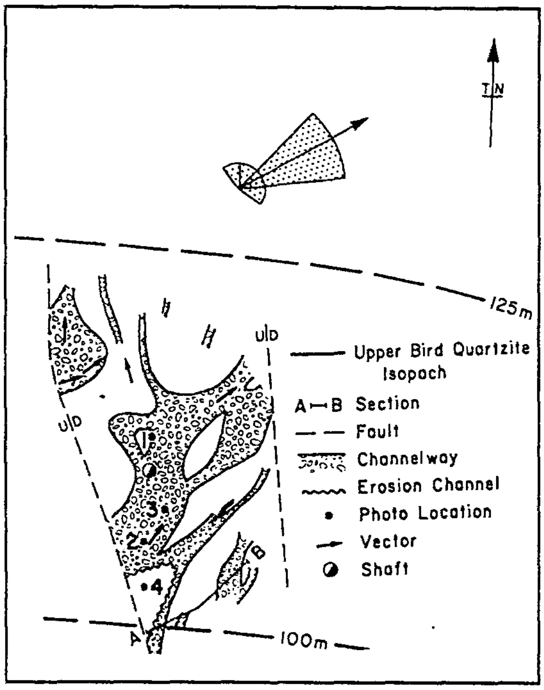


Figure 35 *Details of an area in the northern part of the Welkom Goldfield showing palaeochannels of the B placer superimposed on the Dagbreek Formation isopachs (after Minter,1979).*

Victor (1989) interprets the depositional surface of the "B' Reef as an undulating, rippled shaly bottom of a water body. He regards the deposition of the "B" Reef conglomerate as taking place by avalanching and preferential accumulation of pebbles at the toe of the foreset slope of a partly sub-aqueous alluvial fan front. Victor (op.cit) believes that under this kind of mechanism, any gold present in the bedload would be evenly distributed throughout the thickness of the conglomerate, or accumulate preferentially near the top of the reef. He thus believes that the gold entered the basin of deposition either as a chemical solution or organic association, or both .

Blamey (1991) describes Aandenk Formation sedimentation in the Welkom Goldfield as having a source area to the southwest. He sees the Aandenk Formation as having been deposited by abundant short-lived pulses of sediment into a subsiding basin resulting in argillaceous sediments interbedded with polymictic conglomerates to form an alluvial fan whose channel edges are orientated in a SW-NE direction.

Swart (1992) states that the robust nature of the BPM suggests an increase in tectonic activity on the western margin of the Welkom goldfield. He cites a granite intrusion of Randian age (2726my) to the northwest of the Welkom goldfields as being a possible cause of the tectonic activity. This granite intruded shortly before the end of Witwatersrand sedimentation at a time when the BPM was probably being deposited. This is substantiated by the presence of granite clasts in the BPM, which are not present in the Spes Bona Member.

Swart (1992) states the Reworked BPM is a veneer of bedrock detritus derived from erosional degradation of the BPM. This material was then concentrated by the prograding Reworked BPM fans and braid plain. The Reworked BPM is thought by Swart (1992) to represent distal alluvial plain deposits which were introduced from two separate sources, i.e from the north-west and the north. Swart (1992) states that the thick deposits west of Harmony No 2 Shaft probably represent the amalgamation of longitudinal bars.

Swart (1992) gives evidence at Harmony Gold Mine of movement on the De Bron strike-slip system during Central Rand Group times. This is substantiated by Blamey (1991) who interprets events prior to the deposition of the Uitsig placer at Western Holdings Gold Mine as indicating a small movement on the De Bron Horst.

Several examples are given by Swart (1992) at Harmony Gold Mine which indicate that structures played a major role in providing sites for favourable 'A' Reef sedimentation, or followed "A" Reef trends. He believes that the palaeotopography of the "A" Reef Zone is the most important factor in explaining the highly channelised and erratic distribution of the "A" reef Zone. He also shows that the viable 'A' reef areas are all aligned in a direction that parallels the direction that folds would be expected to develop in if the De Bron strike-slip system was operative during sedimentation. He suggests that the 'A' reef payshoots represent synclines and the unpay zones, culminations. Blamey (1991) however, ascribes the uneven pre-Witpan palaeosurface to preferential compaction of the sediments.

Blamey (1990) states that deposition of the Witpan placer at Western Holdings took place from the northwest. Channels eroded into the footwall and cannibalised pebbles from the braided type pediment placer and introduced them into the basal scour unit.

Lower stream power resulted in deposition of iron rich and other heavy minerals. Reworking by streams caused the scour and degradation in the "reef zone". This was then followed by a transgression and reworking of the upper portions of the reef zone. This resulted in an enrichment of heavy minerals, an increasing pyrite concentration and the highest gold values.

Several authors (Blamey (1991),Swart (1992) and Cadle (1992)) believe that there is evidence of marine processes in the "A" Reef Zone. Cadle *et al.*(1992) believe that the presence of kerogen at the base of Uitsig pebble lags, implies the existence of tidal flats.

Blamey (1991) sees the pyritic zone at the top of the Witpan placer at Western Holdings Gold Mine as being the high energy nearshore zone which overlies the arenite facies (the shelf sand offshore zone). Swart (1992) believes that the sediments of the "A" Reef were deposited on a braided fluvial fan and were reworked by marine processes at the fluvial-marine interface.

Blamey (1991) sees the Uitsig as being a braided deposit reworked by transgression. The carbonaceous material observed on President Steyn mine and Harmony would support a marine environment of deposition for the Uitsig. After the Uitsig event there was an influx of sediment into the goldfield from the southwest. Argillaceous sand was deposited at a reduced rate with the pebbles present being smaller and more dispersed.

Blamey (1991) believes that beach interaction can explain by swash action, the preferential enrichment of gold on only one side of the terraces. In a fluvial environment gold concentrates on both sides of terraces. He believes the more widespread distribution of the pyrite zone and the capping by the siliceous quartzarenite can also be explained in terms of the reworking and shifting of material in a beach environment.

Swart (1992) concludes that the more distal "A" Reef Zone on Harmony Gold Mine is different to that in the proximal Welkom area, because of its bimodal directional structures and other features (Table VII).

Swart (1992) believes that these sediments were deposited in the form of braided fluvial fan and were reworked by marine processes at the fluvial-marine interface.

The HW Grit is not developed in the proximal western parts of the Welkom basin. Towards the northeast of Harmony Gold Mine it is truncated by the Eldorado Formation. It is laterally very extensive to the east. Near Henneman numerous cycles of this deposit can be seen (Swart,1992). During waning flow in a braided

Table VII

DIRECTIONAL FEATURES OF THE

"A" REEF AT HARMONY GOLD MINE (after Swart,1992)

PLACER	REWORKED BPM	WITPAN	UITSIG	'HW GRIT'	UPPER 'A'
THICKNESS TRENDS	SW/NE N/S	SW/NE	W/E NW/SE	W/E	
MATURITY TRENDS	N/S	S/N		S/N	NW/SE
CHANNEL FEATURES	SW/NE NW/SE	SW/NE NW/SE			
CROSSBEDDING				N/S	
RIPPLEBEDDING					N/S
% CONGLOMERATE TRENDS	NW/SE	NW/SE			
MAX. PEBBLE SIZE TRENDS	NW/SE	S/N	S/N		NW/SE
ROUNDED PYRITE ISOPLETHS	NW/SE	SW/NE			
GOLD DISTRIBUTION	NW/SE N/S	NW/SE			

river wedge shaped sand units may build out in the lee of longitudinal gravel bars or infill erosional channels.The last stage in a waning flood is the deposition of thin silt or mud drapes and channel fills in inactive areas (Miall,1977). These features are characteristic of the upward fining sequence of conglomerate to quartzarenite to shale that is found in a typical HW Grit sequence. Swart (1992) believes that the HW grits record a marine transgression with large scale trough-crossbeds resulting from the migration of sand waves and dunes in a tide-dominated continental shelf setting.

Swart (1992) regards the Upper "A" placer as nearshore sediments deposited in a wave dominated setting.

9.4 The Beatrix Reef

Genis (1990) states that the most important characteristic of the Beatrix Reef consideration of a depositional model, is that despite its high bed relief index and abrupt changes in thickness, the reef is essentially a thin gravel sheet overlying an unconformity of regional extent, and is succeeded (disconformably) by a largely arenaceous sequence. Genis (1990) believes that the characteristics of the Beatrix Reef conglomerates and the observed facies sequence associations have been described more commonly from braided fluvial sequences rather than the shallow marine shoreline models proposed by other workers.

Genis (1990) states that the facies associations of the Beatrix Reef (Scour - Gm - Gh - Gt/Gp - St in the facies notation used by Miall,1977) are typical of Miall's (1977) Scott to Donjek types. These gravel deposits however tend to be much thicker and also differ from the Beatrix Reef gravel in that the Beatrix gravels are far more mature, which indicates that they have undergone far more prolonged reworking. The thin sheet-like geometry of the Beatrix Reef implies deposition in a low aggradation rate system in which frequent reworking generates a mature conglomerate layer of limited vertical extent. Genis (1990) favours the fluvial degradation of previously deposited alluvial sequences as being the model most favoured to explain the formation of the Beatrix Reef. The depositional model for the Beatrix Reef as being a placer deposit formed by fluvial degradation in a coarse-grained braid-delta of previously deposited sequences may be typical of most Central Rand Group placers. The deposit formed during a transgressive cycle in response to uplift and erosional degradation. The change to the finer-grained heterolithic facies sequence disconformably overlying the Beatrix Reef, suggests that the fluvial degradation cycle culminated in a transgression of the standing body water (lacustrine or marine) across the braid-plain.

Marine depositional environments are frequently described from the lower parts of the Witwatersrand Supergroup and have recently been proposed as being formative processes for palaeoplacers in the upper parts (Central Rand Group) of the Witwatersrand Supergroup. Shallow marginal marine deposition models overlying transgressive placer forming episodes are proposed to account for many of the Central Rand Group reefs (Main Reef Leader, Vaal

Reef, Kimberley Reefs). Genis (1990) states that a marginal marine transgression across the braid-plain as the culmination to the Beatrix Reef placer forming event is not unique.

The Beatrix placer appears to occupy drainage channels eroded on a pediment beneath the Eldorado Formation fan. The Beatrix placer probably reflects the reworking of underlying placers that outcropped locally and does not represent a renewed supply from an external source. According to Tweedie (1986), the dispersal was northeast, but 25 trough cross-bedding vectors measured by Genis (1990) indicate southwest transport (201°).

10. Evaluation

10.1 Evaluation Techniques

Stear (1986) describes the various valuation techniques and discusses the advantages and the shortcomings of each.

10.1.1 The statistical method

A sample value is taken to be part of a population of all conceivable values in the orebody. Statistical theory assumes that the samples were taken randomly (random values) and independently from the population and that the population exhibits a statistically normal distribution. Because sampling is seldom truly representative, mean value and standard deviation are not true measurements of the population and therefore, they can only be estimated. Tests can then be made of errors or biases, as well as of confidence limits to determine what percentage chance there is of a wrong estimation.

Due to their erratic patterns of concentration, gold values in the Witwatersrand mines do not conform to a normal distribution. Characteristically, the gold value frequency curves display a highly skewed form towards the low grade categories. Because statistical principles can only be applied to normal distributions, or distributions that are manipulated to normality, a logarithmic transformation of the grade categories is made for statistical calculations in the gold mines. The lognormal transformation tends to "smooth" highly variable distributions and to eliminate errors.

As statistical methods merely analyse values as samples all originating from the same probability distribution (a lognormal one on the gold mines), and ignore the spacial distribution of the samples, the problem of "stationarity" is introduced. The stationarity hypothesis assumes that all the possible probability distributions are the same everywhere, which implies that the orebody being evaluated is homogeneous.

10.1.2 The Classical Method

This approach also assumes an homogeneous geological unit of value distribution in which the sample values are related according to their relative positions in space. Weighting factors based on the distance between the sample points are used to produce "smoothed" estimates or trend surface analyses distinguishing high value areas from low value areas. The choice of distance weighting functions is entirely subjective. In practice, where large amounts of data are available, sampling results are averaged arithmetically and weighted into a co-ordinated grid block.

Trend surface analyses are expressed either in contoured form on a map, or as a mathematical equation (regression curve).Because trend surfaces use weighted (linear) averages to smooth the variability in values, it is expected that there will be a random variation (scatter) about the trend of regression. A major constraint to this approach is the assumption that the differences in values between samples is dependent only on the distance between the samples, irrespective of any variations that might exist within the orebody or within the mineralization itself. Trend surfaces are very useful for delineating the spatial distribution or major patterns of gold grade on a large scale, but are not practical for detailed valuation.

10.1.3 The Geostatistical Method

If the differences in values should come from a probability distribution, then that distribution must have a mean (which is the same as saying that it has an average difference in values for a fixed distance) and a variance of the differences of the distribution (known as the variogram). It is assumed in most cases that the average difference (being the average of all the different distances) will be zero in a homogeneous body, except where there is a distinct trend or movement (drift) from high grade to low grade areas in a deposit. Half the average of the variance of the sample difference between pairs of samples for a fixed distance is expressed in graphical form as a semivariogram. The definition of a semivariogram arises, therefore, out of the concepts of "continuity" (homogeneity) and "relationship (constant function of distance) due to position within the orebody". The semivariogram forms the basis of geostatistics. The semivariogram graph is an experimental picture of value data which plots the distance between pairs of values along the horizontal axis and the value of the semivariogram along the vertical axis.

This approach attempts to estimate by weighting sets of samples in accordance with their variation in space. For estimation purposes geostatistics assumes that, in in the absence of trend, the orebody being evaluated will produce a simple, smooth semivariogram curve. This requires that the semivariogram of the data needs to be fitted to a semivariogram model of the deposit, the choice of which is entirely subjective. The accuracy of all estimates are based on the chosen semivariogram model. The de Wijsian model, or straight line model, is most popular in the gold mining industry.

It has been pointed out that the erratic gold distribution and highly variable grades in alluvial gold placers create random errors in sampling representativeness such that the observed grade of the orebody will have an error variance or nugget effect. The nugget effect in the semivariogram simply implies a completely random behaviour of values.

Having fitted a semivariogram model (de Wisjian in the gold mines) an estimate can be made of the unknown values from the known sample values. A measure can also be made of the reliability (accuracy) of that estimate by determining the variance of errors. Given the basic assumptions of no trend and a model of the semivariogram the best (smallest standard error) linear weighted moving average (unbiased) estimator is the kriging technique.

Kriging is a multiple regression procedure that uses the position of the samples relative to one another and relative to what is being estimated to produce the optimum weighted moving average of a block of ground. It considers not only point values but also takes into account the size and shape of the samples and/or areas. Because kriging depends completely on a subjective or estimated model of a semivariogram there is no way of determining by statistical limits of confidence the extent by which the experimental semivariogram differs from the true semivariogram. Hence, an inherent error is present. Errors in geostatistical application are usually introduced because the basic principle of relating data (numerical values) to the known physical and chemical features of the orebody (geology) is being ignored.

Therefore, when applying geostatistical kriging techniques to ore reserve estimations, so as to reduce the potential bias effects that can arise from the use of historical regression curves for block evaluation, a model of the reef is needed which makes sense both statistically and geologically.

Stear (1986) concludes that because kriging depends completely on a subjective or estimated model of a semivariogram, there is no way of determining by statistical limits of confidence the extent to which the experimental semivariogram differs from the true semivariogram. Hence, an inherent error is present. He states that errors in geostatistical application are usually introduced because the basic principle of relating data (numerical values) to the known physical and chemical features of the orebody (geology) is being ignored. He thus believes that when applying geostatistical kriging techniques to ore reserve estimations, a model of the reef is needed which makes sense both statistically and geologically. The more accurately the statistical data can be correlated with the reef characteristics, the greater the level of predictive confidence. Geostatistical evaluation of reef units requires that, the reef zone needs to be transformed from a plan view to a planar or flat orientation where intensely folded, so that the coordinated and gridded reef data used in kriging fits a "true" plane or on-reef coordinate system which is independant of the mine's plan coordinate system. All pertinent geological dislocations such as dykes and faults are digitised from underground plans and transformed where necessary to on-reef coordinates on specific reef planes for the purpose of delineating structurally homogeneous areas prior to defining ore reserve blocks within such areas.

It is clear from the above discussion that the best method of ore reserve estimation is one that uses both sedimentology, (facies analyses) geostatistics (kriging) and structural geology, implying a multidisciplinary approach. A simplified illustration, showing the various stages of how this approach is applied to gold mine valuation, is depicted in Table VIII.

10.2 Case Studies

10.2.1 Western Holdings Gold Mine

A valuation exercise was carried out on the "A" Reef by Blamey (1991) at Western Holdings mine. Sample values were gathered from development chip sampling taken underground and in areas of low density of sampling borehole reef intersections were used. These samples were analysed for gold by "fire assay". Two geostatistical packages (GEOEAS and a AAC in-house package) were used for plotting histograms,log-probability plots and to produce semivariograms.

The normal probability plot of channel width indicated the presence of two normal distributions separated by an inflection point at about 35% cumulative percentage (Fig.38). This inflection point separated the two populations at a channel width of 110cm. The population with a channel width greater than 110cm contains the basal scour and the main reef zone and constitutes ±65% of the dataset. The other population where the basal scour unit is absent comprises ±35% of the dataset. The population representing the pyritic zone cannot be separated from the rest

Table VIII

STAGES IN THE PRODUCTION OF GEOSTATISTICAL VALUATION ESTIMATES ON THE GOLD MINES (after Stear,1986).

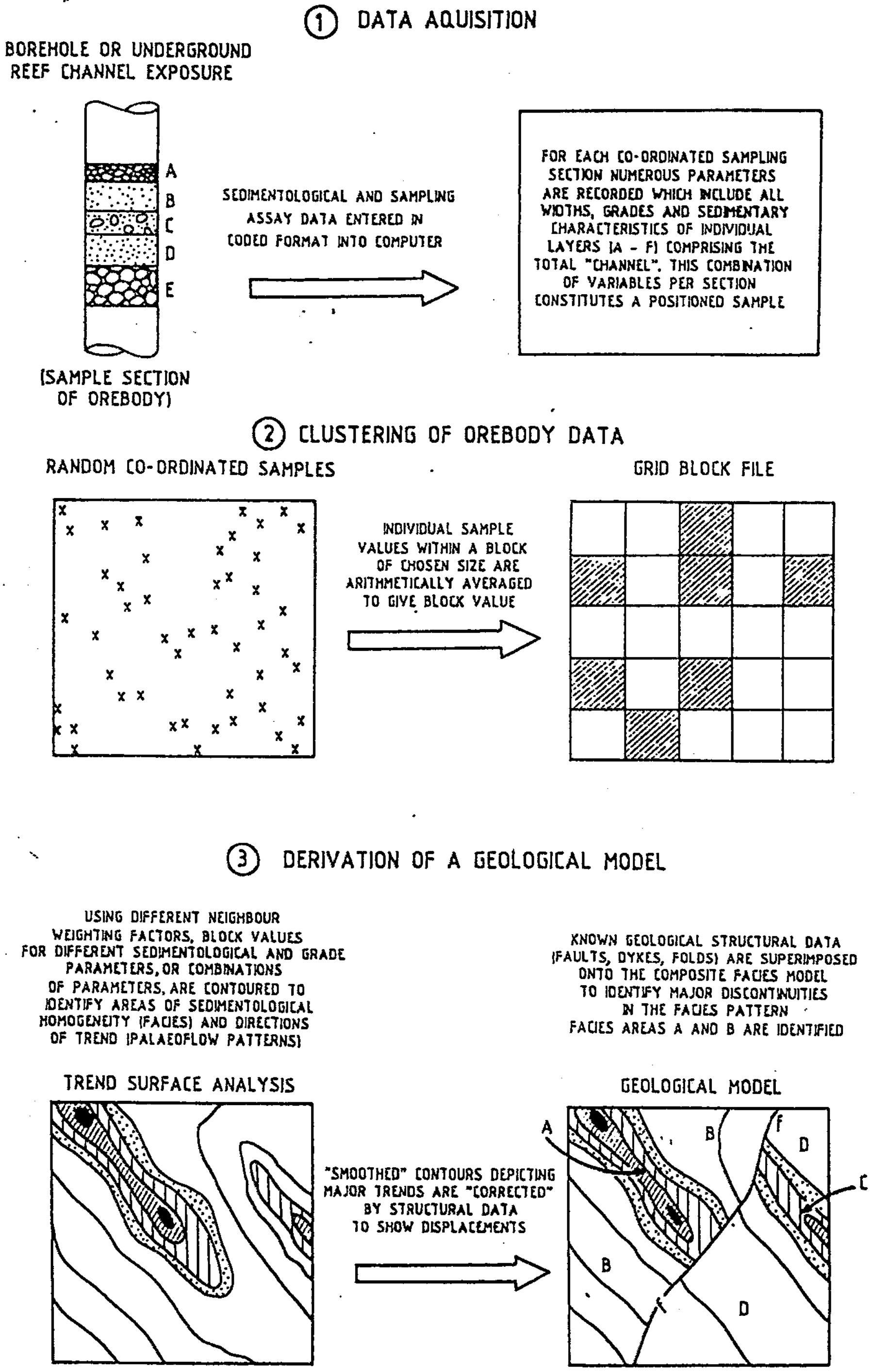
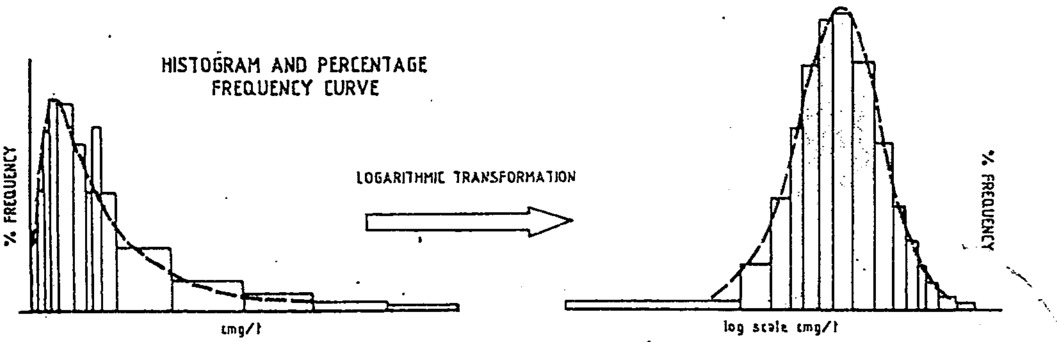


Table VIII(cont)

(4) DERIVATION OF A STATISTICAL MODEL

DATA VARIABLES FOR EACH GEOLOGICAL AREA (DEMARCATED BY MAJOR DISLOCATIONS) AND FOR EACH MAJOR FACIES WITHIN THE GEOLOGICAL BLOCKS ARE ANALYSED INDEPENDENTLY (EG. USING tmg/t AS A VARIABLE)

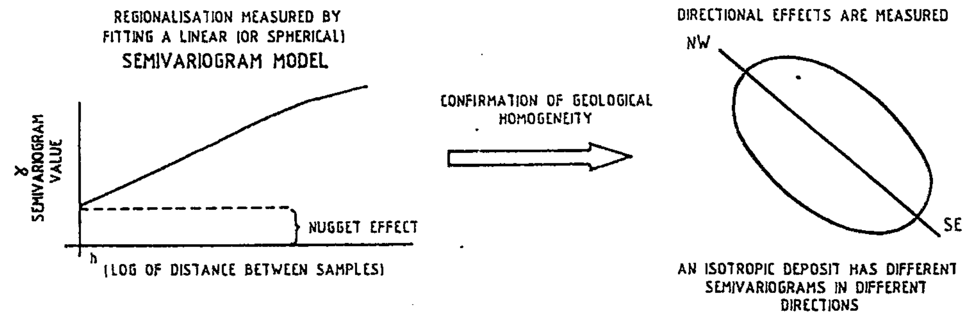


SKEWED DISTRIBUTION

LOGNORMAL DISTRIBUTION

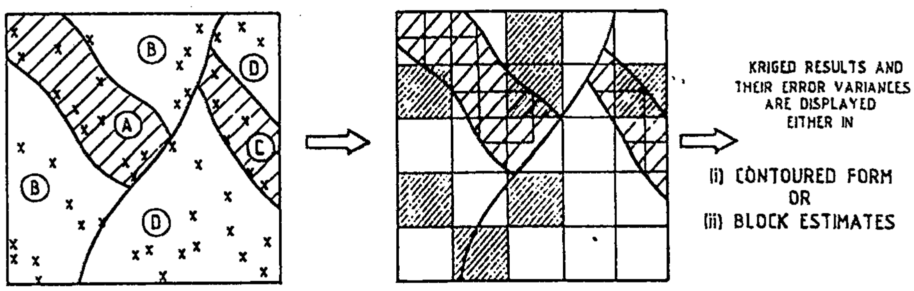
(5) DERIVATION OF A GEOSTATISTICAL MODEL

(FOR EACH AREA OF GEOLOGICAL HOMOGENEITY)
A, B, C, D.



(6) KRIGING

BEST LINEAR UNBIASED ESTIMATOR FOR INTERPOLATING BLOCKS OF UNKNOWN VALUES WITHIN GEOLOGICALLY HOMOGENEOUS AREAS OF THE OREBODY



due to this zone being too thin and widespread.

The distribution for gold values is approximately log-normal. The distribution is bimodal, with an inflection point at ±20 cumulative percent occurring (Fig.37). This indicates at least two gold mineralising controls or processes which may be attributed to the "in-channel" and "terrace" areas (the latter could result in a lower cmg/t value).

The results obtained by Blamey (1991) from the semivariograms can

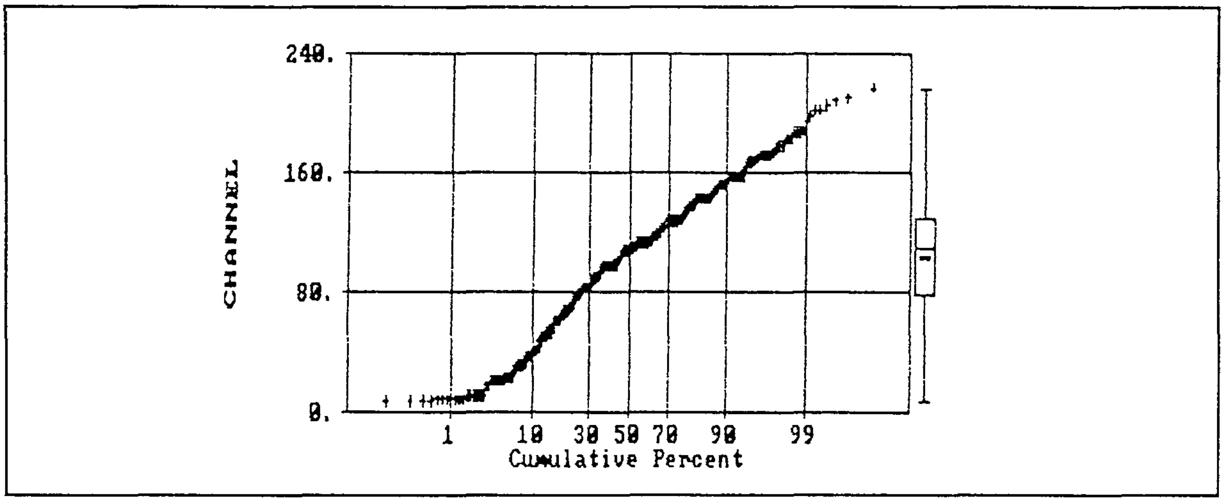


Figure 36 *Normal probability plot of channel width data (after Blamey,1991).*

be accepted with a certain amount of confidence because he has applied the approach that Stear (1986) suggested where he has produced a model that makes sense both statistically and geologically. Using an indicator variogram for gold in cmg/t, he found two trends: a prominent NW-SW trend and a minor SW-NE trend. Blamey (1991) states that the dominant NW-SE trend corresponds to the channel-edge direction recorded during geological development mapping and the weaker SW-NE direction may correspond to gold accumulation on the leading edges of transverse bars. Semi-variogram calculation of channel width confirms the same NW-SE trend. The across-channel (SW-NE) direction semivariogram has a hole-effect at about 100m, corresponding to a subtle wavelength developed between channels within the greater channel complex as exposed at No. 3 Shaft (Fig.38).

Blamey(1991) was able to compile contour plans to graphically

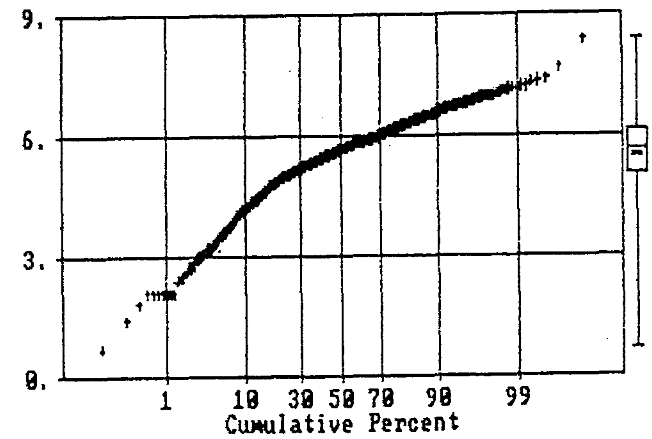


Figure 37 *Log-normal probability plot of gold in cmg/t (after Blamey, 1991)*

represent the data for both channel width(cm) and gold (cmg/t) from kriged block values. From the channel width contour plans he was able to distinguish the areas that only contain the terrace areas (channel width+-50cm) and those that contain all three zones (basal scour unit, reef zone, and pyritic zone, channel width >120cm).

The three components of the Witpan placer that Blamey (1991) recognised (Chapter 4) were not recognised by previous geologists. Blamey (1991) was thus not able to subdivide the sampling data into the three separate subdivisions and to treat them separately during his evaluation exercise. However Blamey (1991) tested the feasibility of subdividing the zones laterally. Channel width values of less than 115cm were called the "reefzone" set and channel width values of 115cm and greater were called the "scour" set. The statistics of each are tabularised in Table IX.

Although the mean cmg/t values are not vastly different, the

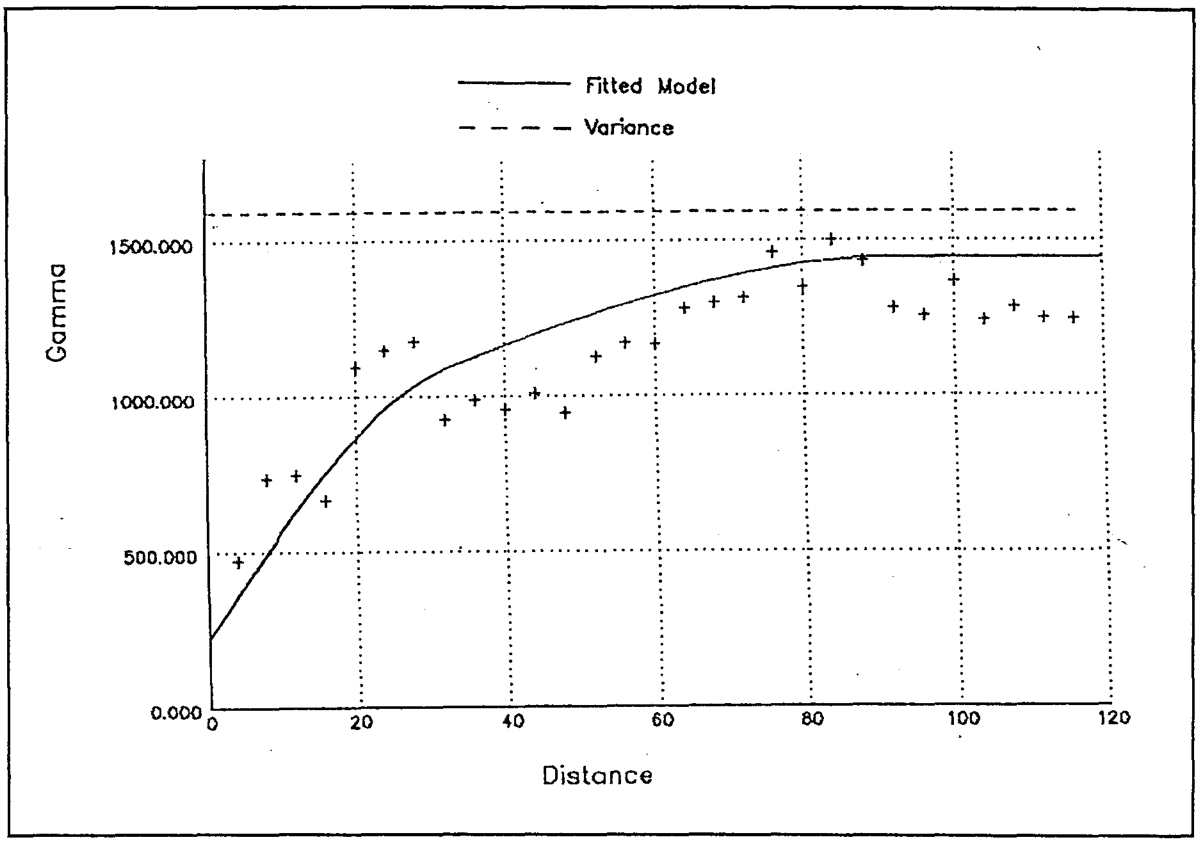


Figure 38 *Semivariogram for channel width (cm) in the SW-NE (across-channel) direction (after Blamey,1991).*

variance and median statistics differ significantly. To weight the zones with their respective cmg/t values during kriging would therefore make little change to any mean grade of a block. The confidence in the value of the blocks will differ due to the variance being significantly different.

Blamey (1991) suggests a valuation technique at Western Holdings whereby the the geologist demarcates the basal scour, reef zone and pyritic zone, and the sampler chips the sample section according to the subdivisions. For the gold values each zone is initially treated as a discrete entity. Classical statistics would be applied to each zone to determine mean cmg/t values and variances. Thereafter semivariograms for gold in cmg/t and Ln(cmg/t) would be modelled. Kriging can then be undertaken for each zone independantly but the results are added to determine a total cmg/t value. The modelled semivariograms and kriging

Table IX

COMPARISON OF DATASETS SEPARATED ON THE BASIS OF 115CM CHANNEL WIDTH FOR GOLD VALUES IN CMG/T (after Blamey,1991)

STATISTIC	SCOUR SET	REEFZONE SET
MEAN	377,5	337,9
VARIANCE	58866	122453
SKEWNESS	1,497	4,116
MEDIAN	331	234

routines can be applied on a monthly basis. Selective kriging, using a package which allows for single and irregularly shaped areas is essential. The area stoped is digitised and entered into the computer and that area alone is kriged.

10.2.2 Harmony Gold Mine

At Harmony Gold Mine the Witpan and the Uitsig placers lie in close proximity to or adjacent to each other and thus both are evaluated. Davies and Hatherly (1989) illustrate that, since the Witpan and Uitsig placers have different sedimentological features and gold concentrations, separate semivariograms need to be drawn up for each placer when evaluation takes place. An averaged semivariogram will not accurately reflect the underlying variances of the orebody and will lead to loss of accuracy in evaluation exercises. Improved evaluation estimates can be expected by recognising the placer type at the time of sampling and treating the two data sets separately. The results can then be combined for an "A" Reef estimate.

11. Discussion

Within this literature study certain aspects of the structural controls and sedimentology of the "B", "A" and Beatrix Reefs seem to show a consistent relationship with their gold tenor. These aspects have been observed in other placer deposits within the Witwatersrand basin and are important when exploring for and evaluating Witwatersrand placer deposits.

1) The presence of unconformities - The "B", "A" and Beatrix Reefs are all located directly above unconformities, which become disconformities away from the edge of the basin. Other unconformity related gold and uranium placer deposits are the Basal/Steyn and Leader Reef placers in the Welkom Goldfield, the Vaal Reef placer and Elsburg No. 5 Reef placer in the Klerksdorp Goldfield, the Carbon Leader zone, Deelkraal Reef Zone and the Ventersdorp Contact Reef in the West Rand Goldfield, the Main Reef Leader and the South Reef placer in the Central Rand Goldfield, the U.K.9 Zone in the East Rand Goldfield and the Kimberley Reef placer in the Evander Goldfield (Beater,1982).

2) Types of placers - Although popular opinion is that the "B", "A" and Beatrix Reefs were all formed as gravel-bars in braided, fluvial channels, they differ from the earlier gold reefs mined in the Welkom Goldfield (the Basal and Leader Reefs) in that they generally tend to be low grade and their mineralization tends to be confined to channels. This means that these placers have to be mined selectively, that strict grade control is necessary and that the application of sedimentology and geostatistics with the aid of a computer package is often essential. Pretorius has identified five different types of"reefs" that have been exploited in the Witwatersrand basin. These are given in Table X. It is important when exploring for mineralised placers in the Witwatersrand basin to be able to identify each different type of placer.

3) The distribution of the gold mineralization - When evaluating

the more channelised placers during mining and exploration it is important to have an understanding of the distribution of the mineralization in the orebody. Witwatersrand gold deposits generally tend to have a negatively skew log-normal distribution. This can result in errors when evaluating a potential ore deposit or mining block in exploration and mining respectively, resulting in an economic orebody being discarded , or the orebody being mined at a loss. The shape of the distribution curve of the particular orebody can influence the size and spacing of samples underground during mining or boreholes during exploration.

Table X

Types of exploited Witwatersrand reefs (after Pretorius,1989)

<u>stratiform horizons containing gold and uraninite</u> :

- in thin, clast-supported conglomerates, formed as lag-gravels on fluvially-scoured surfaces
- in thick, clast-supported conglomerates, formed as gravel-bars in braided, fluvial channels
- in pyritic quartzites ('bpq') in scour-channels
- on parting-planes or unconformity-surfaces devoid of pebbles or kerogen
- in kerogen bands ('carbon seams') on unconformity-surfaces

12.Conclusion

The Welkom Goldfield was discovered through :

1) Knowledge of the existence and host rock stratigraphy of the gold placer deposits in the Central Rand and Klerksdorp areas.
2) The perseverance of early prospectors (Allan Roberts in particular).
3) The use of geophysical instruments (the magnetometer and torsion balance) to delineate the approximate position of the Central Rand Group sediments in which the gold reefs were likely to be found. This was used in siting the most promising localities for drilling.

The sedimentary rock sequences in the Central Rand Group represent unconformity bounded, genetic packages. The unconformities are defined by the well-known stratigraphic markers called Leader Reef, B Reef, Big Pebble Marker, and VS 5 (Rosedale), and they onlap each other, to the south and west, up the stratigraphic sequence. The Basal/Steyn, Leader, Eldorado ,Beatrix, Beisa, "A" and "B" are the economically mineralised gold and uranium placer deposits that occur in the sequence at various parts of the goldfield, with the Basal/Steyn having been the most significant in terms of gold production. The structural configuration of the goldfield is one of a north- to south-trending synform that is split near its axis by two major faults. These two faults, the De Bron and the Homestead, form a triangular-shaped Central Horst block that structurally divides the goldfield into a western , Odendaalsrus , section and an eatsern , Virginia, section.

The "B" Reef lies on an unconformity at the base of the Spes Bona Formation. Lithologically it varies considerably over the Welkom goldfield from a thin lag a few centimetres thick to a package several metres thick in the northern part of the Welkom Goldfield, and from a polymictic to an oligomictic conglomerate. Minter (1978) describes the "B" Reef as being confined to discrete, interconnected channelways. The "B" Reef is erratically mineralised, with the mineralization often associated with "flyspeck" carbon, thin carbon seams or buckshot pyrite at the base of the reef. Mullins *et al.*,(1986) have described three different facies of the "B" Reef at Loraine Gold Mine. Kingsley regards the "B" Reef fanhead deposits.

Mining and exploration for the "A" Reef has only become important from the early 1980's in the Welkom goldfield and is now mined on six mines. The "A" Reef placers vary from continuous sheetlike units to discrete channel systems. The "A" Reef is generally described as being a reef couplet consisting of two placers, the Witpan and the Uitsig, although Swart (1992) has included the underlying "Reworked BPM" and the overlying "HW" Grits and the" Upper A" placer into his "A" Reef Zone. The "A" Reef Zone reaches a maximum thickness of over 9 metres and 7 metres at Loraine and Harmony Gold Mines respectively. Towards the south and south-west the package becomes progressively thinner. At Western Holdings Gold Mine Blamey (1991) regards the Witpan placer as being due to an initial channeling event to produce a "basal scour unit", reworking by anastomosing braided streams to produce the "reef unit" followed by a transgression which caused a reworking of the upper portions of the reef zone to form the highly mineralised "pyritic zone". Blamey regards the source area as being to the northwest. Swart (1992) at Harmony Gold Mine regards the Witpan placer as being an alluvial plain and braided stream deposit with the source area being to the southwest respectively. Swart regards the Uitsig placer as being a braided plain deposit ,the "HW" Grit granule conglomerate as recording a marine transgression and the Upper "A" placer as nearshore sediments deposited in a wave dominated setting.

The Beatrix Reef lies at the base of the Eldorado Formation on an unconformity surface overlying the Virginia Formation in the southern part of the Welkom Goldfield. It is a placer unit varying from a single pebble lag to multiple layers forming a package up to 3 metres in thickness (Genis,1990). Three facies of the Beatrix Reef have been recognised. The upper and lower have been correlated with remnants of the Aandenk Formation, and the VS5 placer respectively. The middle facies consists of scour based oligomictic conglomerate layers and grey, trough-crossbedded quartz arenites. Palaeocurrent indicators and pebble size distribution suggest a transport direction towards the south-south-west. Gold concentration tends to be associated with unconformities in association with lag conglomerates, along flanks of channels and along the top contact of the reef.

The origin of gold in the Witwatersrand basin can be classified into three main groups:
1) The modified placer theory in which the gold and heavy minerals were washed into the basin by fluvial agencies and subsequently metamorphosed by thermal fluids of unknown origin.
2) The syngenetic theory in which gold was introduced by precipitation from a solute complex in surface waters.
3) The epigenetic theory in which gold was introduced by hydrothermal solutions that ascended through the porous, clastic sediments.

From the distribution of basin edge unconformities it can be deduced that the Welkom fan depository was tectonically active on the western, southern and eastern margins during sedimentation. Palaeocurrent studies indicate that sediment was transported predominantly from the south and west. Kingsley (1992) states that all of the Welkom placers and genetic sequences can be explained in terms of a dynamic interplay between tectonic uplift, transverse alluvial fans and longitudinal braid plain sedimentaion. Jordaan believes that the seven palaeoplacers in the Aandenk and Spes Bona Formations in the Welkom Goldfield were all deposited in a braided stream environment.

Evaluation of Witwatersrand deposits can be done by three techniques. These are the Statistical technique, the Classical technique and the Geostatistical technique (Stear,1986). The statistical technique does not take into account the position of the sample taken and assumes that all the probability distributions are the same everywhere. In the classical method the sample values are related according to their relative positions in space. Weighting factors based on the distance between the sample points are used to produce trend surface analyses. A major constraint to this problem is the assumption that the differences in values between samples is dependent only on the distance between the samples, irrespective of any variations that might exist within the orebody or within the mineralization itself. The advantage of the geostatistical method is that the reliability of a particular estimate can be made by determining the variance of errors. Because kriging depends on the subjective modelling of a semivariogram, it is necessary when evaluating an orebody, to produce a model which makes sense both statistically and geologically. At Western Holdings Gold Mine probability plots of channel widths and gold grades for the "A" Reef (Blamey,1991) were able to distinguish several populations which were identified as separate facies of the Witpan placer. The mapping and evaluation of these facies separately using a computer-based geostatistical package will result in a more accurate evaluation of the "A" Reef.

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