ECONOMIC GEOLOGY RESEARCH UNIT

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Johannesburg

THE NATURE OF THE WITWATERSRAND GOLD-URANIUM DEPOSITS

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INFORMATION CIRCULAR No. 86

UNIVERSITY OF THE WITWATERSRAND

JOHANNESBURG

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by

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May, 1974

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ABSTRACT

The Witwatersrand Basin was filled with 13 900 metres of sediments and volcanics in the period between 2 500 and 2 750 million years ago. The depository took the form of a yoked basin, with a fault-bounded, active, northwestern edge, and a gently downwarping, more passive, southeastern edge. The basin was enclosed, and had dimensions of at least 350 km, in a northeasterly direction, and 200 km in a northwesterly direction. Six major goldfields and several smaller mineralized areas have been discovered since 1886. Of the order of 150 mines have been operative at one time or another, and from these 2.8 billion tons of ore have been mined up to the end of 1972. The total gold recovered amounted to 28 722 metric tons, valued at a little under US$ 34 billion, and the total uranium to 76 012 metric tons, valued at more than $2 billion. The average gold content of the ore mined to the end of 1972 was 10 ppm and the average uranium tenor 280 ppm. The distribution of goldfields is intimately related to the pattern of interference folding that produced structural depressions and culminations, the latter in the form of domes of basement granite. The folds are accentuated by major faults parallel to the axial plane traces of the folds. The same interference pattern controlled the morphology of the floor of the basin, influenced the nature and distribution of the sediments, and deformed the strata after they had been laid down. The goldfields are all located in the downwarps between the domes, and all take the form of fluvial fans, or fan deltas, which preferentially developed on the northwestern edge of the basin, at the interface between a fluvial system bringing sediments from the source-area and a lacustrine, or inland-sea, system which distributed the material in the basin. The depository, as a whole, had a regressive history, shrinking with time and displacing the apices of successive fans farther and farther into the basin. Uplift of the source-area along the basin-edge was a continual process in the mechanism of sedimentation, with the result that the fanhead sections of early fans were subjected to elevation, erosion, and reworking into later fans. This repeated reworking resulted in the development of economic concentrations of gold and/or uranium on at least 16 different horizons in the stratigraphic column. Each of these horizons straddled a plane of unconformity which separated the terminal phases of one cycle from the initial stages of a succeeding cycle of sedimentation. The top members of the earlier cycle were fine sands, silts, or muds, frequently with algal mats, that settled in a delta-flat or estuarine environment as a transgressive sequence of sedimentation started giving way to a regressive phase. Gold, uranium, and other heavy minerals were concentrated on the unconformity. The bottom members of the later cycle were generally conglomerates, formed as openwork gravels into which auriferous sands subsequently washed, as the depositional energy-level decreased. In many instances, the conglomerates also incorporated into their matrices gold and uranium concentrated on the underlying finer sediments or in the filaments of the algal mats. The source of the gold was in ultramafic and mafic igneous rocks of Archean greenstone belts older than 3 250 m.y., while the uranium was drawn from the granites which intruded the greenstones between 3 050 and 3 200 m.y. ago. The mineralization is unequivocally the response to sedimentary processes.

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THE NATURE OF THE WITWATERSRAND GOLD-URANIUM DEPOSITS

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THE NATURE OF THE WITWATERSRAND GOLD-URANIUM DEPOSITS

THE ECONOMIC SIGNIFICANCE OF THE WITWATERSRAND BASIN

The Witwatersrand Basin ranks as one of the greatest mining fields the world has ever known. It has been estimated that, of all gold mined in all countries in all parts of the world, over the whole span of recorded history, about 55 per cent has come from the auriferous sediments of the Witwatersrand sequence of rocks. Gold-bearing conglomerates were first discovered in March, 1886, near where the city of Johannesburg is now located, and in the 88 years that have elapsed since then, no less than about 150 mines, of varying size and importance, have exploited the sedimentary concentrations of heavy minerals. In 1953, recovery started of the associated uranium mineralization. A very high level of mining activity still prevails within the confines of the basin, and it has been calculated that the depository contains the world's largest reserves of gold-bearing ore and among the world's largest reserves of low-grade uranium ore. Current projections indicate that mining operations will still be in progress at the end of the century.

The basin is located in the northeastern part of the Republic of South Africa, within the provinces of the Transvaal and the Orange Free State. The approximate centre of the presently known basin is at 27°E and 27°S. The area underlain by Witwatersrand strata has a roughly ovoidal shape, with a long axis stretching 350 km in a northeasterly direction, and a short axis 200 km in a northwesterly direction. The northwestern rim of the basin, to which the mining activity is restricted, runs for a distance of 500 km from near the town of Evander in the northeast to near the town of Welkom in the southwest. Mining operations have reached a maximum depth of 3 600 m below surface, and core-drilling has penetrated to a maximum depth of 4 600 m. In certain sections of the basin, particular stratigraphic horizons have been mined out completely for 70 continuous km along strike and for 8 km down dip.

From all the boreholes that have been drilled, shafts that have been sunk, tunnels that have been excavated, and stopes that have been mined, a volume of data has been gathered over the 88 years that is staggering in its dimensions. A single, large-sized, deep-level mine, at the end of its life, will have been sampled at certainly no less than 10 million points, at each of which the metal content, the thickness of the mineralized horizon, and the number of bands comprising the horizon will have been measured. At many of these points, other geological information will also have been recorded. It is probably correct to say that from no other Precambrian sedimentary basin in the world has so much information been gathered with respect to the inter-relationships between stratiform mineralization, structure, stratigraphy, and sedimentology.

The production of gold from South Africa during the past ten years and the total value of sales of such gold are shown in Table 1. Of the annual amount of gold won in the country, approximately 98 per cent comes from the Witwatersrand Basin, the main source of the balance being mineralization in the Archean greenstone belts. Peak production was realized in 1970, when just over 1 000 metric tons of gold were mined, and US$ 1.164 billion were realized from sales. The quantity of gold extracted each year since then has been declining steadily, but the value of sales has increased substantially, due to the rising price of gold on the free market. In 1973, revenue from gold sales amounted to $2.563 billion.

The place which South Africa occupies in the ranks of the world's gold-producing countries can be seen in Table 2, which was compiled for the year 1972. The contribution from the U.S.S.R. is an estimate only. Of a total output of almost 1 368 tons, South Africa's share was a little under two-thirds. It is truly remarkable that one sedimentary basin can so dominate the pattern of distribution of a particular metal in the earth's crust.

THE WITWATERSRAND BASIN IN TIME AND SPACE

Age of the Witwatersrand Strata

Except for the very basal members of the succession, no age measurements have been obtained on any of the strata that compose the Witwatersrand Sequence. Lavas in the lowermost section of the stratigraphic column have been dated at 2 820 ± 55 million years, by the Rb/Sr method, and at 2 800 ± 60 m.y., by the U/Pb method. The Witwatersrand rocks rest on Archean basement granites which have

TABLE 1

GOLD PRODUCTION AND SALES OF GOLD IN SOUTH AFRICA 1964-1973

Year	Gold Recovered kilograms	Sales Value billions $	$/kilogram
1973	852 325	2.563	3 007
1972	908 725	1.633	1 797
1971	976 297	1.259	1 289
1970	1 000 417	1.164	1 163
1969	972 956	1.126	1 158
1968	967 146	1.099	1 136
1967	949 679	1.075	1 132
1966	960 466	1.087	1 131
1965	950 332	1.073	1 129
1964	905 470	1.023	1 129

TABLE 2

ESTIMATED WORLD GOLD PRODUCTION : 1972

	Kilograms Gold	Percentage
1. South Africa	908 700	66.43
2. U.S.S.R.	186 000	13.60
3. Canada	64 700	4.73
4. U.S.A.	45 900	3.36
5. Australia	30 000	2.19
6. Ghana	22 700	1.66
7. Philippines	18 200	1.33
8. Rhodesia	15 500	1.13
9. Japan	7 500	0.55
10. Colombia	5 700	0.42
Elsewhere	63 000	4.60
TOTAL	1 367 900	100

yielded two ages - 2 900 ± 50 m.y., by the Rb/Sr method, and 3 100 ± 100 m.y., by the U/Pb method. Stratigraphically well above the top of the Witwatersrand succession, lavas belonging to the Ventersdorp Sequence have been dated at 2 300 ± 100 m.y.

Uraninite grains in the mineralized arenaceous horizons have given an age of 3 040 ± 100 m.y., and monazite grains one of 3 160 ± 100 m.y. Both of these ages are older than that of the lowermost members of the Witwatersrand succession, pointing to the fact that these minerals are of a detrital origin, and are not the products of epigenetic mineralization of the sediments. These ages provide valuable evidence in the old placer-hydrothermal controversy regarding the origin of the gold and uranium mineralization.

From such meagre data, it has been put forward that the age of the Witwatersrand Sequence is between 2 500 and 2 750 m.y. These rocks rest on a granitic basement which has a probable age of 3 050 - 3 200 m.y. From this basement was derived the detrital uraninite which forms a characteristic constituent of some of the economically exploitable horizons within the Witwatersrand succession. There is a suggestion that a later granite (2 800 - 2 950 m.y.) intruded into this basement. A conspicuous lead loss in the uranium minerals has been dated at 2 000 - 2 100 m.y., a period which is believed to mark the beginnings of magmatic activity associated with the emplacement of the Bushveld Igneous Complex. An earlier metamorphic overprint on the Witwatersrand strata is thought to be a product of Ventersdorp volcanic activity which probably took place between 2 250 and 2 500 m.y. ago.

Proterozoic Basins and the Pattern of Crustal Evolution

The Southern African sub-continent is built about two ancient Archean nuclei which are located in the eastern part of the region. One of these is located between Lesotho, northern Natal, and the eastern Transvaal, and the other in Rhodesia. These nuclei are constituted by granite-greenstone terranes which have different ages for the last periods of regional metamorphism. The older nucleus is contained within the Kaapvaal Craton, in the northeastern part of South Africa, which suffered its last major metamorphic event between 3 000 and 3 250 m.y. ago. The younger nucleus forms the basement of the Rhodesian Craton which reached a stable state possibly 2 750 - 3 000 m.y. ago.

Most of the Archean formations on the Kaapvaal Craton were deposited under marine conditions. The topmost members of the Archean stratigraphy - the Moodies clastic sediments and intercalated non-clastic and volcanics - represent the emergence from below sea-level, and the first indications of continental-type sedimentation can be seen at a time somewhere round 3 250 m.y. From then on, supracrustal development in the Proterozoic took the form of shallow-water basin formation, with no indications of deep marine conditions having played any role. The strata were laid down in fluvial, deltaic, and shelf environments. Crustal instability is reflected in the volcanic members that are associated with all the Proterozoic sediments that were laid down on the Kaapvaal Craton.

Between 3 250 and 1 750 m.y. ago, five separate Proterozoic basins were formed on the Kaapvaal Craton. The locations of the depositional axes of each of these are shown on Figure 1. The Pongola Sequence is the oldest of the basins, but the Moodies rocks, assigned to the Archean, have many of the characteristics of the later basins. The age of the Pongola rocks has been considered to be between 2 750 and 3 000 m.y., but there are indications that the lower limit might lie between 3 100 and 3 200 m.y. The Pongola Sequence is succeeded by Witwatersrand strata (2 500 - 2 750 m.y.), Ventersdorp rocks (2 250 - 2 500 m.y.), Transvaal formations (2 000 - 2 250 m.y.), and the Waterberg strata (1 750 - 2 000 m.y.). There is no preserved record of further Proterozoic sedimentation on the Kaapvaal Craton, and the next sequence of strata, covering all the above-mentioned rocks, belongs to the upper half of the Paleozoic.

It would appear that the five Proterozoic basins all have the general geometry of yoked basins. The depositional axes were originally oriented east-northeastwards, and the fault-bounded, more unstable side of the depositories was always to the northwest of the depositional axes. The southeastern margins of the basins were much less active, and downwarping, rather than downfaulting, was the preferred mode of tectonic adjustment. It can be seen in Figure 1 that there is a migration of the basin axes northwestwards with time, and that there is a younging of Proterozoic depositories from the Caledon gravity low in the southeast to the Limpopo gravity high in the northwest. The northwestern active side of each basin was buried beneath the more passive edge of the succeeding basin.

The transition from Archean- to Proterozoic-style of crustal evolution took place on the Kaapvaal Craton at between 3 000 and 3 250 m.y. ago. On other shield areas of the world, the age of the transition has been dated at about 2 500 m.y. Continental conditions thus started to prevail in Southern Africa about 500 m.y. before they became apparent elsewhere. The Witwatersrand Sequence was deposited during these 500 m.y., and it is thought that this is one of the major factors

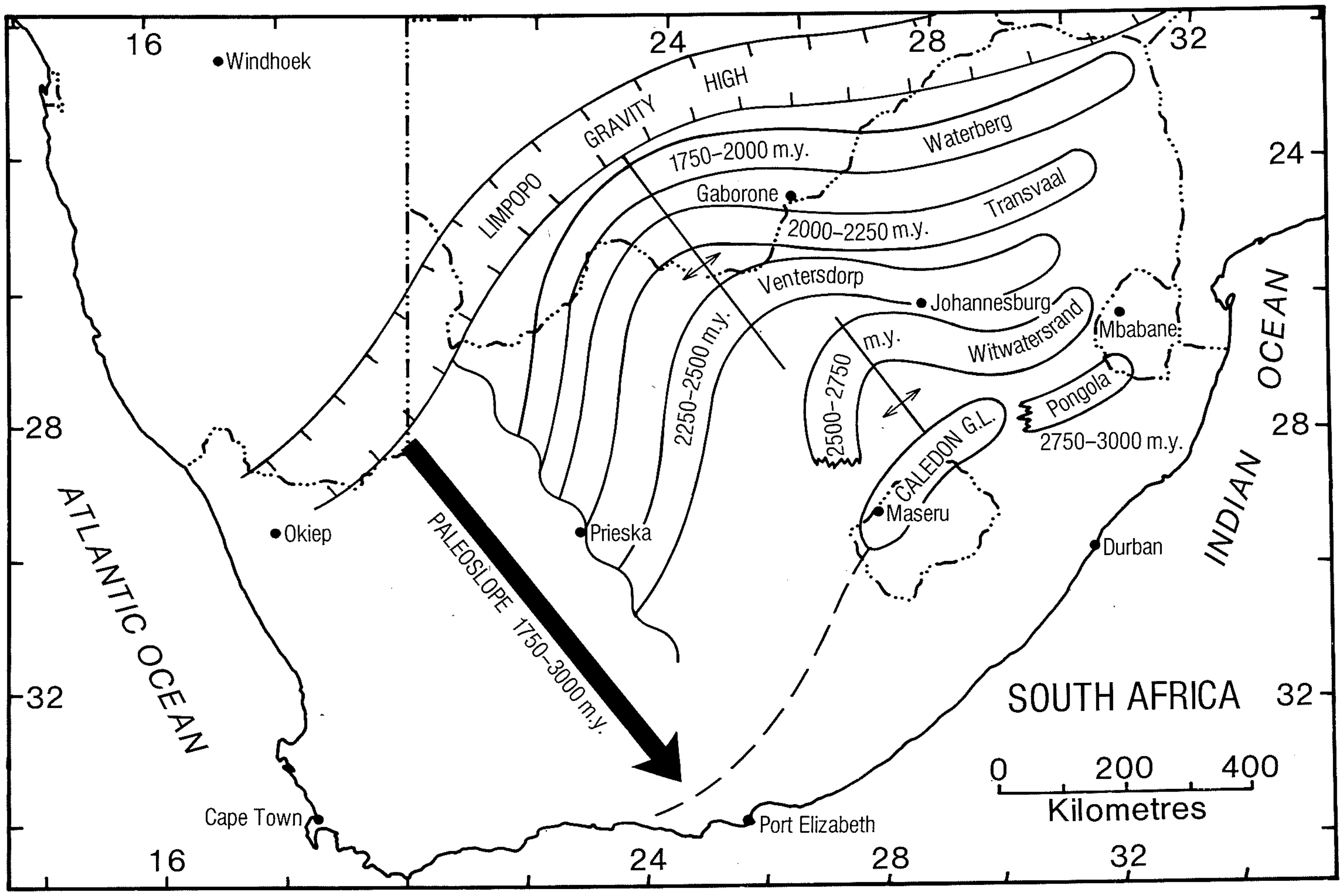


Figure 1 : *The relative positions of the depositional axes of progressively younger Proterozoic sedimentary basins on the Kaapvaal Craton in the northeastern part of South Africa. The basins young up the regional paleoslope from the Caledon gravity low towards the Limpopo gravity high. The full extensions of the Pongola and Witwatersrand basins still remain to be determined beneath the Phanerozoic cover.*

contributing to the uniqueness of the Witwatersrand Basin and its contained gold and uranium mineralization. Greenstone environments were still to the fore elsewhere in the world when optimum conditions for Witwatersrand, continental-type sedimentation were operative on the Kaapvaal Craton.

THE ARCHITECTURE OF THE WITWATERSRAND BASIN

Structure and Components

The Witwatersrand Basin is filled with approximately 14 000 metres of sediment and volcanics which have been folded into an asymmetrical synclinorium. The dips of the strata on each limb, but particularly the northwestern one, decrease stratigraphically upwards. Very steep dips, and even overturning, might be present in the lowermost members of the succession, while the beds at the top might be inclined at angles of less than 20 degrees. Two main directions of deformation have resulted in the present configuration of the basin, as portrayed in Figure 1 - folding about axial plane traces which trend between northwest and north-northwest and traces which lie between northeast and east-northeast. Superimposition of the two trends has resulted in an interference pattern, the regional manifestation of which can be seen in the broad arcuation of the Witwatersrand and other Proterozoic basins along a northwesterly-trending continental arch.

By far the greater proportion of the Witwatersrand rocks lies beneath a younger cover of Proterozoic and Phanerozoic formations, as can be seen in Figure 2. Overlying strata can be either conformable or unconformable on the Witwatersrand Sequence, which, in turn, rests on the Archean basement with a sedimentary contact along a grand unconformity representing a hiatus of up to 500 m.y. The best exposures of Witwatersrand rocks lie along the flanks of the various basement granite domes which have their optimum outcrop along the northwestern rim of the basin and in the northeastern section of the depository. Considerable tectonic movement has taken place along the contacts between the Witwatersrand formations and the granite domes, and, on some of the latter, the basement has been remobilized to give the appearance of being later than the Witwatersrand rocks. The most conspicuous example of this is on the Vredefort dome where the younger strata have suffered high-grade metamorphism and intense structural deformation.

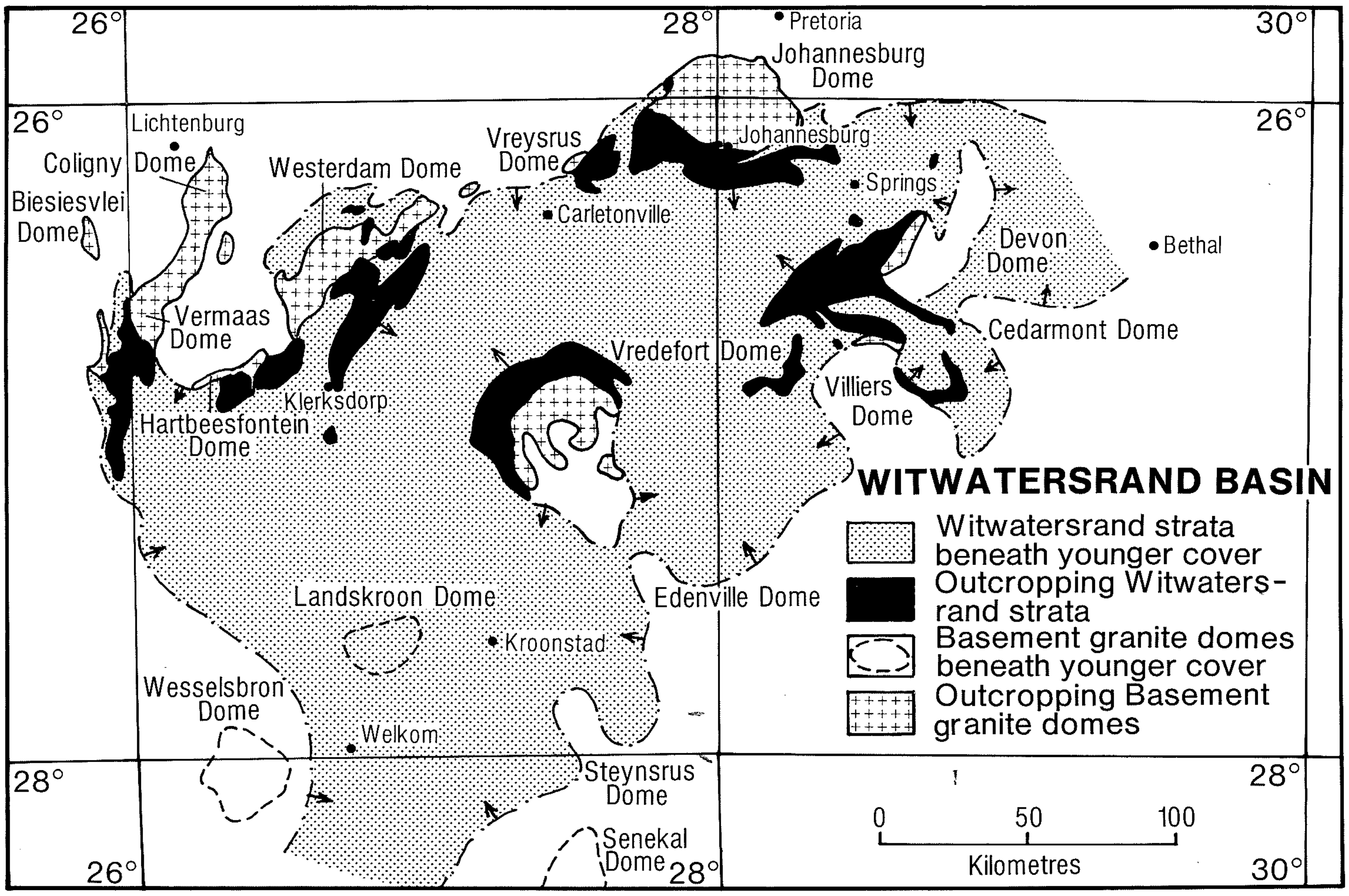


Figure 2 : *The outcrop pattern of Witwatersrand strata and basement granite domes. The position of the outcrop and sub-outcrop of the base of the Witwatersrand Sequence has been determined by surface mapping, by magnetometric and gravimetric geophysical surveys, and by coredrilling.*

Within the basin are six major goldfields, the positions of which are outlined in Figure 3. The presence of three of these fields - Klerksdorp, West Rand, and East Rand - was indicated by outcrops of the auriferous horizons. The other three goldfields - Welkom, Carletonville, and Evander - have no surface representation, and were located beneath a younger cover of up to 3 000 metres by gravimetric and magnetometric geophysical prospecting and by deep coredrilling. In earlier Witwatersrand literature, the Welkom Goldfield is referred to as the Orange Free State field, the Carletonville Goldfield as the Far West Rand field or the West Wits Line. The Central Rand field, in which the gold-bearing strata were first discovered, and which is located about the city of Johannesburg, is now taken to be a geographic term used for the area of common overlap of the West Rand and East Rand goldfields.

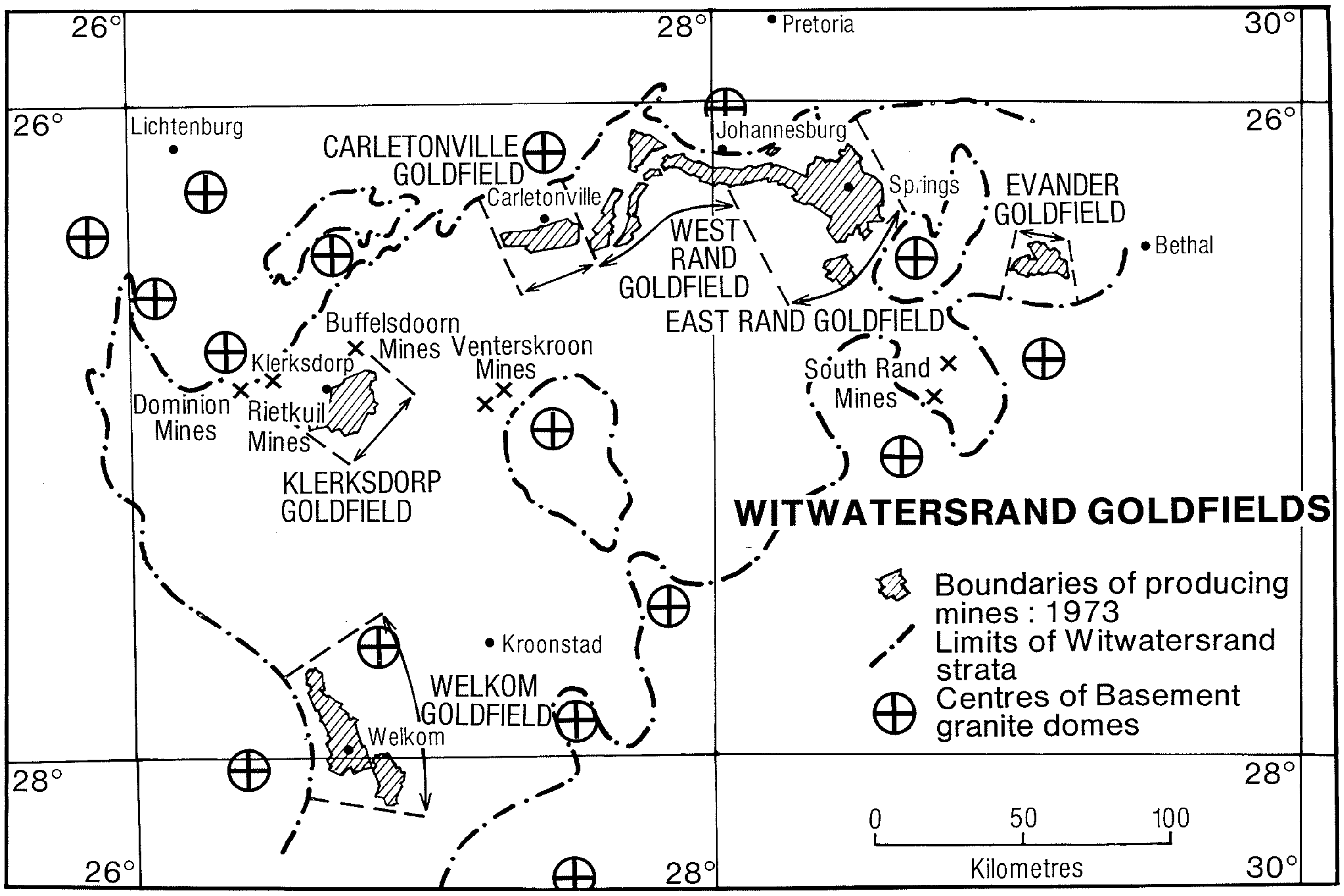


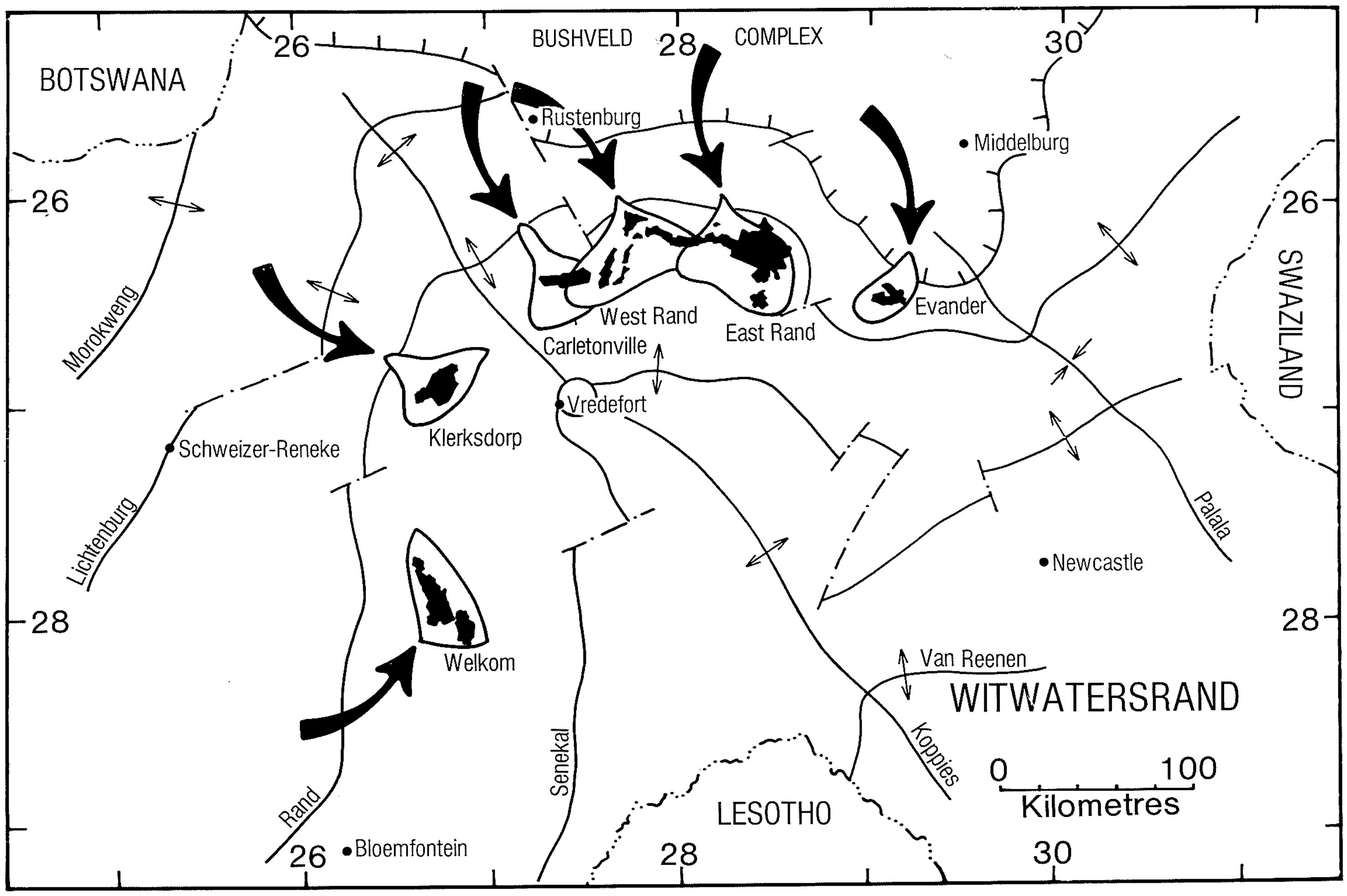
Figure 3 : *The location of the major goldfields and the minor mineralized areas in the Witwatersrand Basin. The boundaries of current mining activities within each goldfield are shown, as well as the locations of the goldfields in synclinal downwarps between basement granite domes.*

In addition to the six major goldfields, there are five smaller areas where limited amounts of gold have been won in the past. The Dominion mines, Rietkuil mines, and Buffelsdoorn mines, shown in Figure 3, can be regarded as subsidiary sections of the Klerksdorp Goldfield. The defunct Venterskroon mines are located on the northwestern flank of the Vredefort dome, and proved to be of the same limited economic significance as the South Rand mines. This latter group of old workings can be regarded, in some respects, as the extreme southeastern portion of the East Rand Goldfield.

The centres of the basement granite domes have been plotted in Figure 3 in relation to the various goldfields. It is apparent that each of the six fields is situated in a downwarped segment of the basin between the domes. The Welkom Goldfield is positioned between the Wesselsbron, Landskroon, and Senekal domes; the Klerksdorp Goldfield between the Hartbeesfontein, Westerdam, and Vredefort domes; the Carletonville Goldfield between the Westerdam, Vreysrus, and Vredefort domes; the West Rand Goldfield between Vreysrus and Johannesburg domes; the East Rand Goldfield between the Johannesburg and Devon domes; and the Evander Goldfield between the Devon and Cedarmont domes.

Pattern of Folding

The main fold components of the Witwatersrand Basin and surrounding country are shown in Figure 4. The northwesterly-trending flexures have retained a relatively straight disposition, whereas the northeasterly traces reflect considerable bending about the former. It would appear



<u>*Figure 4*</u> : *The relationship between goldfields, fluvial fans, and major fold axes in the Witwatersrand Basin. The arcuate shape of the basin is the result of the two superimposed directions of folding, and has been formed about the northwesterly-trending Koppies continental arch. The arrows indicate the direction of transportation of sediment from the source-area in the northwest to the basin.*

from this relationship that the northwesterly folds are younger than the northeasterly, but there is abundant evidence that both fold directions were active before, during, and after Witwatersrand sedimentation, and they have been mutually interactive throughout all phases of the structural history of the basin. The northeasterly folds, which are longitudinally parallel to the depositional axes of the Proterozoic sedimentary basins, belong to the Vaal trend; the transverse, northwesterly folds are members of the Orange trend. The interaction of these two trends has produced the Vosfi Pattern - the Vaal-Orange Superimposed Fold Interference Pattern. The geometries of deposition, preservation, and exposure of all the Proterozoic rocks, not only those of the Witwatersrand Basin, on the Kaapvaal Craton are the responses to deformational processes which acted within the framework of this interference pattern.

In Figure 4, only the first-order regional folds have been shown. These now form sub-continental arches and downwarps. Conspicuous arcuation, concave to the southeast, is developed along the Koppies anticline, of the Orange trend, while a lesser intensity of arcuation, concave to the northwest, is apparent along the Palala syncline. The regional plunge on these transverse folds is obviously to the northwest, in the same direction as the younging of the Proterozoic basins.

The five dominant anticlines of the longitudinal, Vaal trend - the Morokweng, Lichtenburg, Rand, Senekal, and Van Reenen folds - show a progressively greater tightness of their hinge-zones from northwest to southeast. This increasing constriction of the cores of the Vaal folds along the transverse Koppies arch culminates in the severe deformation and metamorphism of the Archean and Proterozoic rocks of the Vredefort Dome.

On a lower order of interference, the Vosfi Pattern has given rise to the many structural culminations - where anticlinal traces intersect anticlinal traces - and structural depressions - where syncline intersects syncline - which are apparent in Figures 2 and 3. The most obvious examples of the synclinal downwarps between the lines of domes can be seen in the northwards protuberance of Witwatersrand rocks southwest of the Vermaas dome and in the southwards embayment between the Villiers and Cedarmont domes. The periodicity of the transverse folds is measurable in the following distances between the traces of anticlines running through the domes : between Wesselsbron and Senekal-Landskroon-Hartbeesfontein-Vermaas-Biesiesvlei, 55 km; between Senekal-Biesiesvlei and Steynsrus-Southwest Westerdam-Coligny, 40 km; between Steynsrus-Coligny and Edenville-Vredefort-Northeast Westerdam, 50 km; between Edenville-Northeast Westerdam and Vreysrus, 50 km; between Vreysrus and Villiers-Johannesburg, 45 km; and between Villiers-Johannesburg and Cedarmont-Devon, 45 km. The wavelengths of the longitudinal anticlines are as follows : between Biesiesvlei and Vermaas-Coligny, 40 km; between Vermaas-Coligny and Hartbeesfontein-Westerdam, 50 km; between Westerdam and south of Potchefstroom, 45 km; between south of Potchefstroom and Vredefort, 45 km; between Vredefort and south of Koppies, 50 km; and between south of Koppies and Edenville, 50 km.

This second-order fold pattern, which controls the distribution of basement domes and major goldfields, has average periodicities of 40-50 km for both the longitudinal and the transverse folds. The transverse continental arches have wavelengths of between 400 and 500 km. Detailed structural investigations in the South Rand area (Pretorius, 1964) have shown that smaller-scale sedimentological and tectonic features have periodicities of 4-5 km; 1.5-2.5 km; and 0.5-0.8 km. The overall regional frequencies of folds are affected by the size of, and amount of vertical movement on, the granite domes which form on the structural culminations. Where large domes are formed, as in the Vredefort and Johannesburg instances, more lower-order, tighter folds are developed as the dome is approached. These smaller-scale folds often have a marked influence on localized sedimentological features, such as the formation of fluvial channels and the concentration of heavy minerals.

The locations of the existing goldfields are intimately related to the larger-scale structure, as depicted on Figure 4. With the exception of the Evander field, all the goldfields are located immediately southeast of the axial plane trace of the Rand anticline. The original basin was contained between the Lichtenburg and Van Reenen anticlines, and by far the greater part of the presently preserved strata is to be found between the Rand and Senekal anticlines. There is repeated evidence pointing to the fact that the post-depositional regional structures, which account for the pattern of present preservation, are reactivations of the same structures that controlled the geometry of sedimentation during Witwatersrand times, and of the same structures that moulded the morphology of the pre-Witwatersrand surface.

Pattern of Faulting

Faulting is very closely associated with folding. The most important of the array of faults that affect the strata are the strike faults which run parallel to the depositional axis of the basin and to the longitudinal, Vaal trend of folds. This type of fault is well illustrated in the Klerksdorp Goldfield (Figure 5). The Buffelsdoorn, Kromdraai, and East Buffelsfontein faults follow the same trend as the edge of the basin and the syncline which has a closure on Stilfontein Mine. A graben is developed between the Buffelsdoorn and Kromdraai faults and a horst between the Kromdraai and East Buffelsfontein faults. A syncline and an anticline, respectively, lie between these same faults, giving an example of a structural feature that is the rule within the Witwatersrand basin, viz. blocks of elevated ground are generally horst-anticline structures, while downwarped blocks are usually graben-syncline structures.

The major strike faults are typically normal faults, with the downthrown side towards the depositional axis of the basin. The amount of vertical displacement on these faults is of the order of 1 000 - 2 000 metres, but a displacement of almost 5 000 metres has been recorded. The strike faults are invariably accompanied by parallel, anthithetic, normal faults which dip towards the plane of the major strike faults. The result of this association is that the strata are disposed in elongated blocks of varying width, which are wedge-shaped in a vertical section.

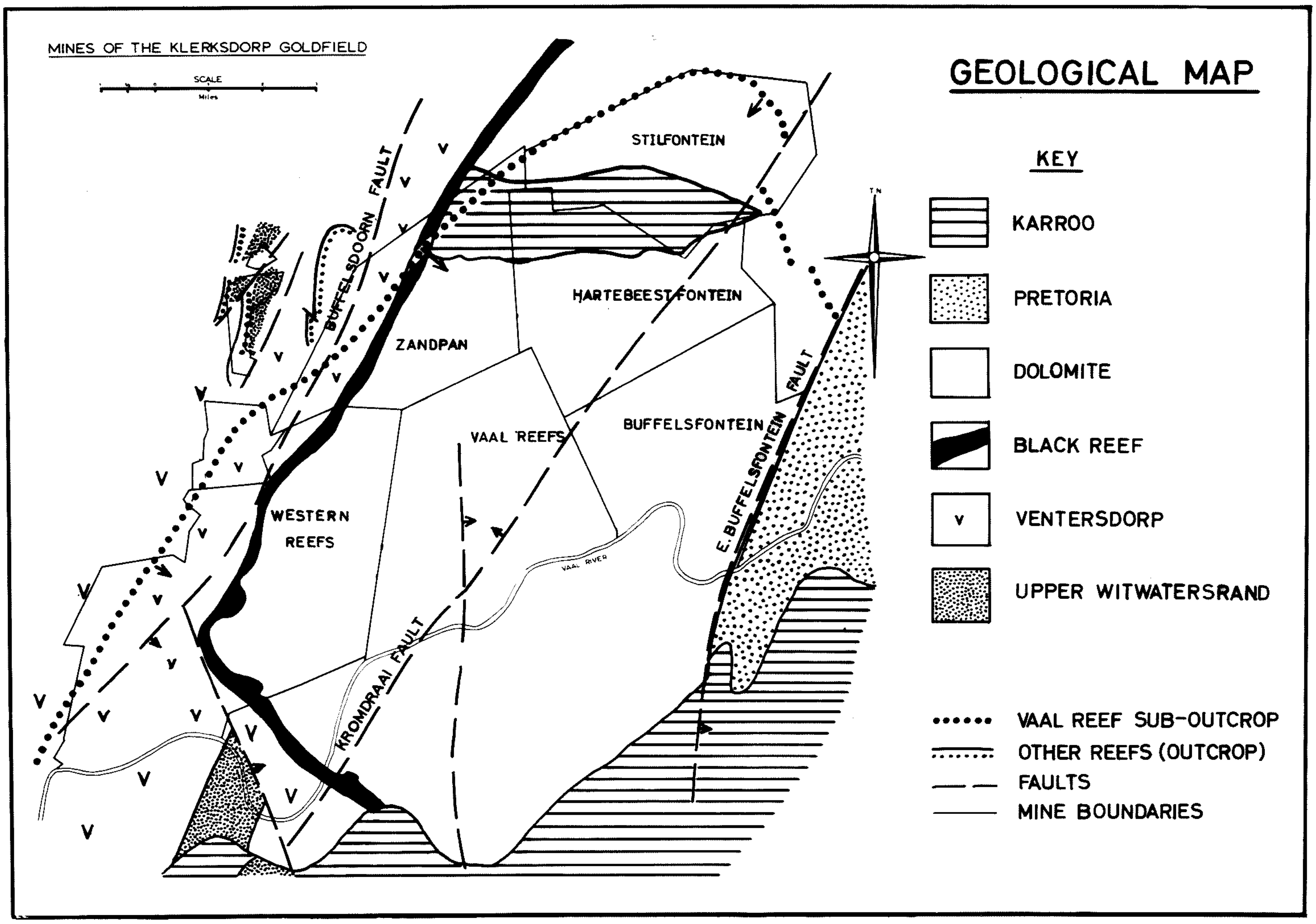


Figure 5 : *The structure of the Klerksdorp Goldfield (after Minter, 1972). The basin-edge strike faults can be seen to run parallel to the axial plane traces of the folds. Grabens contain synclinal downwarps and horsts anticlinal upwarps. The boundaries of the main deep-level mines are shown.*

The pattern of strike faults is shown in Figure 6, which portrays the more important structural elements of the South Rand area. The Sugarbush Fault is an example of the normal strike fault. A short distance south of it is another persistent strike fault, and then, farther to the south, are several parallel faults, of shorter length, which dip towards the Sugarbush Fault. This arrangement is repeated in a group of faults south of Deneysville-Greylingstad. The area also serves the purpose of illustrating the overall complexity of faulting which is ubiquitous in the Witwatersrand Basin, and also the outcrop pattern resulting from the interplay of the fault regime and the series of alternating folds from the Deneysville Syncline, through the Villiers Anticline and the Balfour Syncline, to the Waterval Anticline. The types and the frequency of each among the total of 95 observed displacements in the area have been analysed in Table 3, which can be considered representative of the nature of faulting to be found throughout the Witwatersrand Basin.

That vertical tectonics, associated with the rising of the granite domes, has played a significant part in the deformation of the basin can be detected in the variations in vertical displacement along the Sugarbush Fault. The northern side is the downthrown side. The displacement is 1 070 metres at the western extremity of the portion of the dislocation shown in Figure 6, and this increases progressively to a maximum of 4 880 metres adjacent to the Devon Dome. This differential uplift of 3 810 metres takes place over a distance of 40 km. There is also a less impressive indication of the effects of vertical tectonics on the nose of the Villiers Anticline, where this appears in the base of the Upper Witwatersrand strata, just north of the Sugarbush Fault.

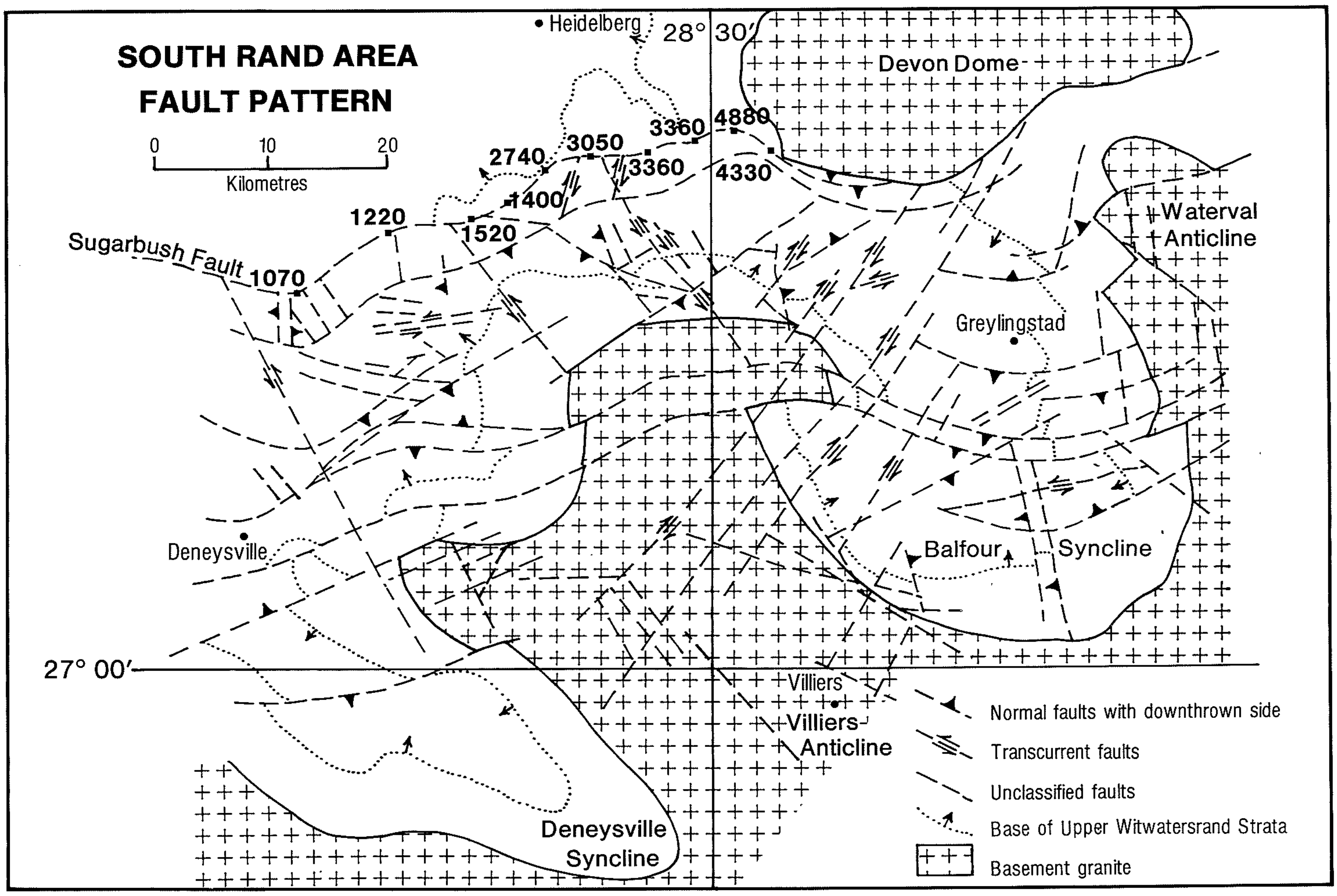


Figure 6 : *The complex pattern of folding and faulting along the south-eastern margin of the basin in the South Rand area. The northwesterly-trending folds are well displayed. The major east-west faults are coupled with antithetic, parallel faults. The vertical displacements on the Sugarbush Fault are given in metres.*

On the axial plane trace, the amount of displacement is 1 520 metres, whereas the movements on either side of the hinge of the fold are 1 220 and 1 400 metres.

The long history of deformation in the basin and the changes in the stress fields can be discerned in the imprints of different movements on the same fault plane. The strike faults are believed to have been the planes of weakness along which the crust foundered to form the yoked basin that subsequently filled with Witwatersrand sediments and lavas. Differential movement between the uplifted edges of the depository and the subsiding floor continued, spasmodically, down these faults for the entire period of basin formation. As subsidence of the basin, as a whole, progressed and a space problem was created in a vertical sense, stratigraphically higher strata started to ride upwards and outwards along bedding planes, in compliance with adjustment according to the tenets of concentric folding. At the same time, some of the strike faults, which had been acting as normal, gravity faults, were reactivated as high-angled reverse dislocations to assist in the upward movement of material from the inner sections of the basin. With the rising of the granite domes, a further space problem was created, with lateral as well as vertical overtones. Strata squeezed between adjacent domes adjusted by horizontal movement along the strike faults, so that, after having served as normal and reverse faults, these dislocations suffered a third re-activation as transcurrent or wrench faults. With the onset of the succeeding period of basin development, the strike faults again moved according to a normal gravity pattern. Related to the folding of the beds, many of the earlier fault planes were also flexured, so that sinuous fault traces are characteristic of most of the longitudinal dislocations.

TABLE 3

TYPES AND FREQUENCY OF 95 FAULTS IN THE SOUTH RAND AREA

Strike of Fault	Type of Fault	Percentage of Total
N 75 W	normal	8
N 60 W	normal	6
N 30 W	left-lateral	18
N 10 W	reverse	19
N 10 E	right-lateral	4
N 40 E	right-lateral	12
N 60 E	reverse	13
N 80 E	left-lateral	6
N 80 E	normal	14

SOURCE OF WEALTH IN THE WITWATERSRAND BASIN

In 1971, South Africa celebrated the centenary of its mining industry, and the opportunity was taken to assess the total value of minerals or mineral aggregates that had been recovered from each of the geological formations which constitute the total stratigraphic spectrum of the country. The Witwatersrand Basin witnessed its first sustained mining in 1886, so that Table 4 is an evaluation of the first 85 years of exploitation of the contained mineral deposits.

TABLE 4

TOTAL VALUE OF MINERAL PRODUCTION FROM WITWATERSRAND BASIN
1871-1971

Product	Sales Value (millions $)
1. Gold	31 557.492
2. Uranium	2 183.777
3. Silver	109.856
4. Pyrite	79.149
5. Platinoids	11.402
6. Building Stones	6.300
7. Diamonds	0.019
TOTAL	33 947.995
% of South Africa's Production : 1871-1971	68.78

Up to the end of 1971, almost 69 per cent of the gross value of all minerals produced in South Africa had come from the Witwatersrand Basin. Of a grand total of a little under $ 34 billion, gold had been responsible for 93 per cent of the output of mined products from the basin. Uranium recovery, which had been in operation for only 18 years, accounted for $ 2 billion. The balance of the realized mineral wealth came from silver, pyrite, platinoids, building stones, and diamonds.

With the exception of the building stones, the source of the revenue came from a limited number of narrow stratigraphic horizons, called reefs, distributed erratically through the 14 000 metres of the succession. These reefs are in no way analogous to those encountered in carbonate sedimentology. They represent mining terminology for any bed or portion of a bed in the Witwatersrand Sequence, which carries gold and/or uranium mineralization that can be economically exploited. The understanding of the nature of these reefs and the environments in which they formed is the objective of most geological work undertaken in the Witwatersrand Basin.

STRATIGRAPHY AND LITHOLOGY

Succession and Thickness

The full succession of members comprising the Witwatersrand Sequence is not present in any one locality in the basin. One or more groups are missing either completely or partially, due to depositional onlapping or erosional removal. Table 5, therefore, represents a composite stratigraphic assemblage of all the groups that are present at various localities. The Dominion Group, for instance, can be found only around the Vredefort Dome and from the Klerksdorp Goldfield westwards. Only the lower part of the Klipriviersberg Group is present in the northeastern portion of the presently known basin. All members of the Lower Witwatersrand succession have not been found in the Evander Goldfield and surrounding area. Controversy still exists as to whether the Dominion Group is the basal member of the Witwatersrand Sequence or whether it belongs to an older succession of rocks, and as to where the uppermost Witwatersrand volcanics end and the basal lavas of the succeeding Ventersdorp Sequence begin. Many of the boundaries between groups comprising the Lower and Upper Witwatersrand divisions are quite arbitrary, and have not been related to specific episodes in the sedimentological history of basin development. Despite all that is known, there is still ample room for revision of the stratigraphic classification of the Witwatersrand Sequence.

TABLE 5

COMPOSITE STRATIGRAPHICAL THICKNESSES AND RATIOS OF WITWATERSRAND SEQUENCE FROM TYPE AREAS OF DEVELOPMENT

Group	Total metres	Volcanics metres	Quartzites metres	Shales metres	Sand:Shale Ratio	Volcanics:Sediments Ratio
Klipriviersberg	3 050	2 740	130	180	0.7	8.8
Kimberley-Elsburg	1 670	0	1 640	30	54.7	0.0
Main-Bird	1 490	300	1 010	180	5.6	0.3
Jeppestown	1 380	420	410	550	0.8	0.4
Government	1 970	0	1 240	730	1.7	0.0
Hospital Hill	1 620	0	610	1 010	0.6	0.0
Dominion	2 720	2 650	60	10	6.0	37.9
Klipriviersberg	3 050	2 740	130	180	0.7	8.8
Upper Witwatersrand	3 160	300	2 650	210	12.6	0.1
Lower Witwatersrand	4 970	420	2 260	2 290	1.0	0.1
Dominion	2 720	2 650	60	10	6.0	37.9
Witwatersrand	13 900	6 110	5 100	2 690	1.9	0.8

The ratio of volcanics:sediments is a pointer to the general order of infilling of all the Proterozoic basins on the Kaapvaal Craton in South Africa. The Witwatersrand Basin had an initial period of high crustal instability in which most of the material entering the basin was drawn from the simatic lithosphere, with only limited quantities of sediments being mixed with the volcanics. The middle stages of basin development were almost devoid of volcanic activity, and continental, shallow-water sedimentation dominated the scene. The terminal phase of the depository was marked by a recurrence of crustal instability and associated volcanism. Sedimentation during this period was also relatively minimal. In the middle period of intensive sedimentation, the ratio of sand:shale increased markedly with time. Higher-energy conditions are believed to have existed in the depository during the laying down of the Upper Witwatersrand sediments than during the accumulation of the muds, silts, sands, and chemical sediments of the Lower Division.

Of the 13 900 metres that comprise the stratigraphic column, there are 5 100 metres of arenaceous sediments, 2 690 metres of argillaceous sediments, and 6 110 metres of volcanic products. The sand:shale ratio is 1.9, and the volcanics:sediments ratio 0.8. The relatively low overall percentage of fine-grained sediments is an indicator of the generally high level of energy that prevailed in the basin during the whole period of its formation, a factor which is of importance in defining the conditions that were uniquely favourable to the generation of the Witwatersrand mineralization.

Nature of Components

The volcanic rocks in the Witwatersrand succession have been described by Whiteside (1970b). The Dominion Group consists of a lower, basic formation (610 metres thick) and an upper, acid volcanic formation (2 040 metres thick). The basic volcanics are underlain by 40 metres of conglomerate, sericitic quartzites, and shaly quartzites, and contain a layer of quartzites, 30 metres thick, near their base. The basic volcanics are composed of andesites, tuffs, tuffaceous breccias, and quartz-feldspar porphyries. The acid volcanics consist of rhyolites, which predominate, and subordinate amounts of andesite, tuff, and volcanic ash. No sediments are present in these upper volcanics.

Two volcanic episodes occurred during the middle period of the development of the Witwatersrand Basin. The Jeppe Amygdaloid occurs within the Jeppestown Group, and is present over almost the whole of the Basin, being absent only in the Johannesburg and Evander areas. The horizon consists of andesites, agglomerates, and tuffs, with intercalated quartzites. A maximum thickness of 450 metres has been recorded, but the volcanics are usually between 30 and 100 metres thick. The Bird Amygdaloid is located near the top of the Main-Bird Group, and has been found only in the portion of the Basin stretching from the East Rand Goldfield to the Evander Goldfield. The main rock-type is a diabase which is considered to represent an altered basalt. Shales and quartzites occur with the volcanics. The maximum thickness is 300 metres, with the normal thickness being of the order of 40 - 110 metres.

The Klipriviersberg Group consists of the Vaal Bend Formation at the base, 915 metres of andesites, pyroclastics, quartz-feldspar porphyries, with associated conglomerates, quartzites, and shales. The upper part of the group is represented by the Langgeleven Formation which is 2 135 metres thick, and is composed of andesites, agglomerates, and tuffs, with minor amounts of sediments. In general, tuffs and agglomerates are more commonly developed in the southwestern half of the basin.

The three end-points in a triangular plot of the composition of the sediments in the Witwatersrand Sequence can be represented by conglomerates, quartzites, and shales. Chemical sediments, in the form of banded ironstones, occur only in the Hospital Hill Group. They represent the products of the lowest-energy conditions in the basin's history, although, in places, carbonate-bearing shales have been reported from the Jeppestown Group.

The shales are usually composed of varying amounts of quartz, kaolinite, pyrophyllite, sericite, chlorite, and chloritoid. Certain shale horizons have a distinctive mineralogical assemblage, and there are also facies variations in the same horizon, which are indicated by variations in the ratios of the different phyllosilicates present. The Kimberley Shales at the top of the Main-Bird Group are frequently very high in magnesium, while the shales of the Lower Witwatersrand Division are unusual in that their sodium content is greater than that of potassium.

Quartzite is a misnomer for the arenaceous rocks which occur throughout the stratigraphic column. Fuller (1958) found that true quartzites occur only in the Hospital Hill Group. The supposed quartzites of the Government and Jeppestown groups are, in fact, sub-greywackes consisting of quartz and chlorite, with small amounts of muscovite and, in several horizons, fine-grained, disseminated magnetite. The quartzites of the Main-Bird and Kimberley-Elsburg groups are, more correctly, hydrothermally altered feldspathic quartzites. Quartz constitutes 70-90 per cent of the minerals, with the balance consisting of muscovite, pyrophyllite, chlorite, chloritoid, and chert. The Main-Bird quartzites are 10-15 per cent higher in silica than those of the other groups. Recrystallized quartzite is present only in the Main-Bird quartzites.

Dykes and Sills

The whole of the Witwatersrand Basin is perforated with dykes and sills, and, by volume, they occupy at least 5-10 per cent of the space in which the basin is set. At least four different ages have been recognized. The Ventersdorp Sequence which follows on the Witwatersrand rocks is characterized by a substantial volume of volcanics, and it is believed that most of the older dykes in the Witwatersrand Basin acted as feeders to the Ventersdorp lavas. The bulk of the post-Ventersdorp dykes and sills are thought to have been emplaced during the igneous activity associated with the Bushveld Complex at about 1 950 m.y. The post-Transvaal intrusions are considered to be contemporaneous with the Pilanesberg period of activity at between 1 250 and 1 350 m.y. The post-Karroo dolerites are Jurassic in age, and belong to the time of great outpouring of basaltic lava as the continents began to break up. The kimberlite dykes are possibly Cretaceous in age.

The various types of dykes and their age-groupings have been summarized in Table 6.

TABLE 6

AGES AND TYPES OF DYKES AND SILLS INTRUSIVE INTO WITWATERSRAND STRATA

Ventersdorp	post-Ventersdorp	post-Transvaal	post-Karroo
epidiorite	dolerite	carbonatite	kimberlite
diabase	quartz dolerite	porphyritic diabase	lamprophyre
amygdaloidal diabase	quartz porphyry	Pilanesberg dolerite	dolerite
quartz diabase	quartz diorite	syenite	
ilmenite diabase	granophyre	elaeolite syenite	
	norite	quartz keratophyre	
	gabbro	diorite	
	pyroxenite		

SEDIMENTOLOGY

Depositional Isopachs

Attempts have been made to reconstruct the Witwatersrand Basin at the time of deposition, in order to learn how extensive the basin originally was, and whether there remains room for undiscovered goldfields to be present. Earlier efforts did not take into consideration the manner in which the strata have been deformed about the transverses arches. Since this information became available, it has been possible to extrapolate to the original basin edges with a fair degree of confidence. However, in a basin where unconformities abound, and where extensive re-working of sediments has taken place from one cycle of sedimentation to the next, there is no reliable way of determining precisely how much material has been eroded from each of the units, the preserved thicknesses of which have been used for the extrapolation.

Figure 7 portrays the postulated depositional isopachs of the Lower Witwatersrand Division, composed of the Hospital Hill, Government, and Jeppestown groups. The maximum thickness of this division was 3 500 - 4 500 metres. The deepest part of the basin appears to have been between the Vredefort and Johannesburg domes. The depositional axis lay on the northwestern side of the Vredefort Dome, contrary to previous conclusions that the dome has been punched up in the very centre of the basin. The contours reflect the arcuation of the whole basin about the Koppies continental arch.

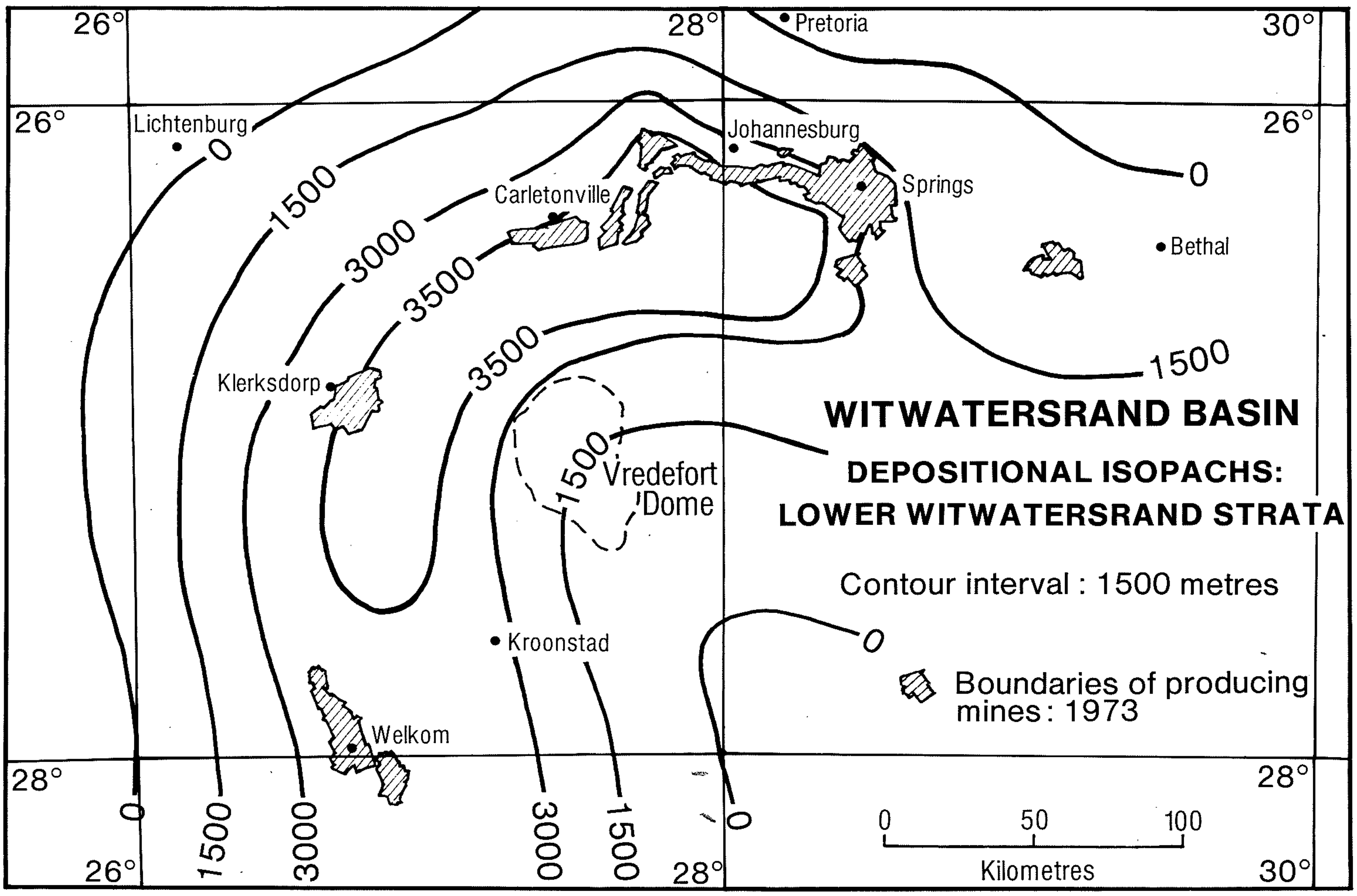


Figure 7 : *The extrapolated depositional isopachs (metres) of the Lower Witwatersrand Division (Hospital Hill, Government, and Jeppestown groups). The locations of the current mining areas with reference to the isopach contours are shown. The isopachs illustrate the arcuate nature of the basin geometry. The Vredefort Dome can be seen to be located well to the southeast of the depositional axis, and not in the centre of the basin, as has been suggested previously.*

The distance between the northwestern zero isopach and the depositional axis was 110 km, and the distance between the axis and the southeastern zero isopach 130 km. Of the original total width of 240 km, there is preserved at present 170 km. On the northwestern side, about 50 km have been eroded away, while on the southeastern side only 20 km have been removed. These figures serve to show the original asymmetry of the yoked basin, and the greater amount of erosion on the more active northwestern edge.

The projected depositional isopachs are depicted in Figure 8 of the Upper Witwatersrand Division, comprising the Main-Bird Group and the Kimberley-Elsburg Group. The maximum thickness of the strata was 3 000 - 3 500 metres. The comments made concerning the location of the depositional axis with respect to the Vredefort Dome, the deepest part of the depository, the shape of the basin, and the arcuation of the Lower Witwatersrand rocks also apply to the Upper Division strata.

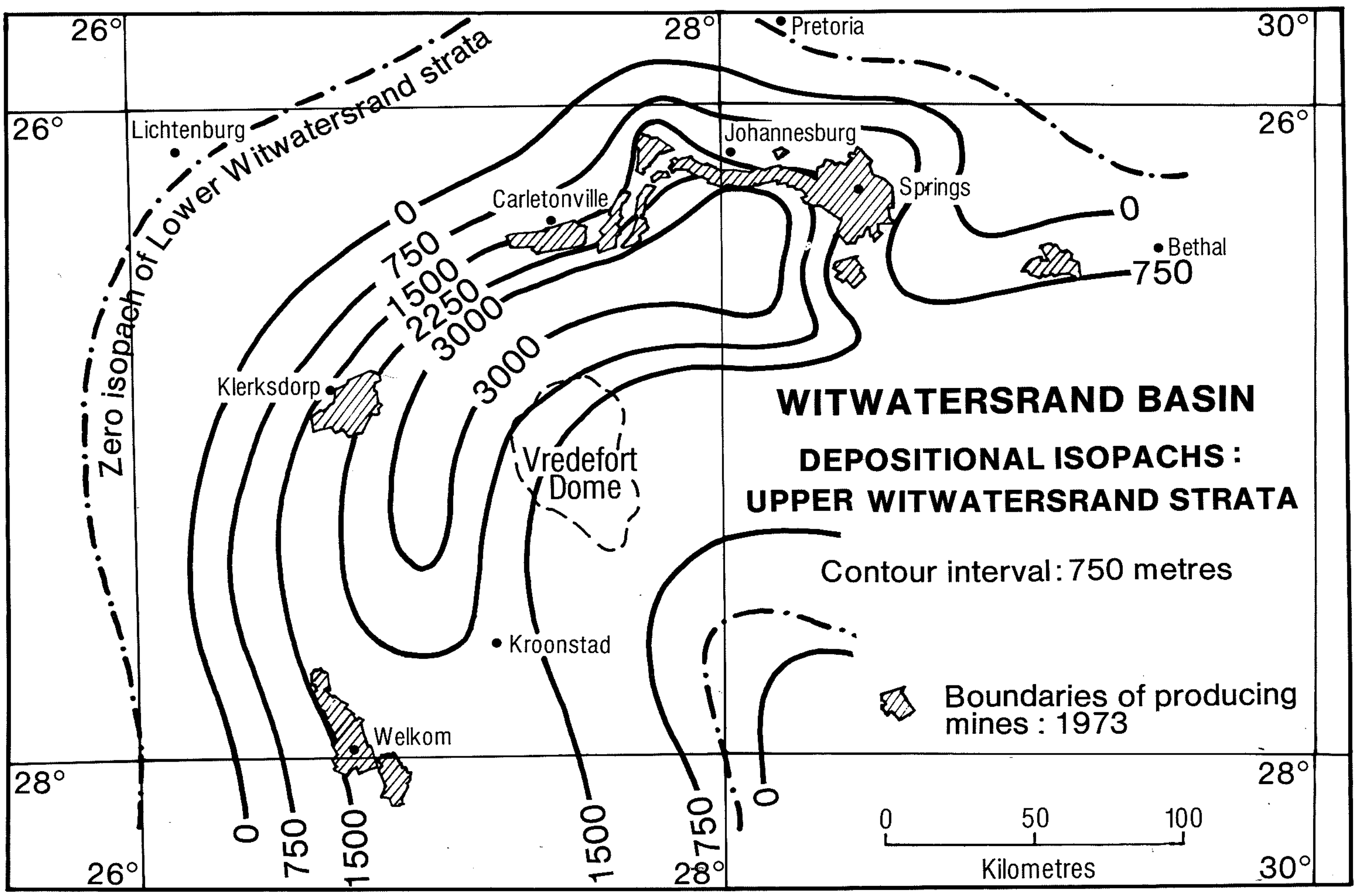


Figure 8 : *The extrapolated depositional isopachs (metres) of the Upper Witwatersrand Division (Main-Bird and Kimberley-Elsburg groups). The generally regressive mechanism of basin development can be seen in the distance that the zero isopach has moved towards the centre of the depository between Lower and Upper Witwatersrand times. The mines are located between the 1 500- and 2 250-metre isopachs, indicating that the mineralized fluvial fans are regressive protuberances into the basin.*

On the northwestern side, the distance from the zero isopach to the depositional axis was 70 km, while, on the southeastern side, it was 140 km. There now remain about 130 km of the original width of 210 km. About 40 km have been eroded on the northwestern side, and about the same amount of the southeastern side.

The isopachs clearly show that the basin was a shrinking depository with time. Between the beginnings of Lower Witwatersrand and Upper Witwatersrand times, the edge of the basin moved southeastwards by about 60 km. The depositional axis moved in the same direction by about 10 km. On the southeastern side of the depository, the Upper Witwatersrand strata onlapped on to the Lower Division. All four features mentioned are characteristic of the mechanism of development of a yoked basin, with one very active fault-bounded side - the northwestern edge in the case of the Witwatersrand basin - and a more passive, slowly subsiding opposite side. In this type of depository, continual uplift on the yoked margin causes previously deposited material to be repeatedly available for reworking into younger beds. It is probable that the major proportion of the missing widths of 40 - 50 km on the northwestern side was represented by sediments that were laid down, uplifted, reworked, and re-deposited during the development of the Witwatersrand Basin, and that only a small fraction was lost due to post-depositional erosion. On the southeastern side, it is likely that the bulk of the missing sediment was removed in post-Witwatersrand times.

The asymmetry of the depository can also be seen in the gradients of the paleoslopes. During Lower Witwatersrand sedimentation, the slope was 1:25 on the northwestern side, and 1:30 on the southeastern side. In Upper Witwatersrand times, the gradients changed to 1:20 and 1:40, respectively. The steeper paleoslope on the northwestern side during Upper Division sedimentation was a contributing factor to the higher-energy conditions that prevailed to give a sand:shale ratio of 12.6 for the Upper Division, compared to 1.0 for the Lower Division.

The contours of the depositional isopachs for each division show that the basin is open to both the south and the east-northeast. The original extent of the depository still remains to be determined, and the full economic potential to be realized.

Fluvial Fans

From numerous studies carried out, in all of the goldfields, of the areal geometry of various stratigraphic horizons, of the patterns of facies variations, of trends in the changes of the grain-size of sediments, of directions and patterns of paleoflow, of the nature of environmental indicators, and of the distribution of heavy minerals, including gold and uranium, it has become apparent that a goldfield represents a fluvial fan, or fan delta. The properties of the sediments constituting the goldfield are transitional between those characteristic of an alluvial fan and of those of the classical delta. Far greater amounts of water were active in the goldfields than are associated with typical alluvial fans, and the energy-level on a goldfield was higher than that which can be recognized in the conventional delta of the Mississippi- or Nile-type. A goldfield is interpreted as having formed at the interface between a fluvial system and a shallow-water, lacustrine, or inland-sea, environment. The provenance area was close to the edge of the depository, the fluvial system was relatively short, the rivers debouched through canyons that remained fixed in their positions for very long periods of time, and the depository was an enclosed continental basin, with no connection to an open sea having yet been found.

From Figure 4, it can be seen that the fluvial fans were all formed on the northwestern, fault-bounded edge of the depository. No large, well-developed fans have yet been found on the southeastern rim of the basin, which was tectonically more passive, and which responded to stress more by downwarping than by downfaulting. The paleocurrent directions indicate that the rivers flowed from the northwest, out of a source-area that now lies buried, for the most part, under the Middle Proterozoic Bushveld Complex.

The fans which have so far been discovered along the northwestern basin-edge are located at the following distances from each other, as measured along the periphery of the depository : Welkom to Klerksdorp, 150 km; Klerksdorp to Carletonville, 120 km; Carletonville to West Rand, 50 km; West Rand to East Rand, 70 km; and East Rand to Evander, 100 km. The irregular distances highlight the overlaps and suggest possible gaps that still remain to be filled. The Carletonville, West Rand, and East Rand fans coalesce in their more distal parts, so that a false impression has been created of great continuity along strike of particular horizons within the stratigraphy. The extensive sheets of gravel that are referred to in earlier accounts of the Witwatersrand Sequence are, in fact, more limited beds of conglomerate that have merged into one another where separate fans have overlapped. The distances between the Welkom, Klerksdorp, and Carletonville goldfields, particularly, indicate possible gaps in the systematic distribution of fluvial fans.

The fans generally have an asymmetrical shape, with the left-hand section, looking from the basin-edge towards the depositional axis, longer and larger than the right-hand section. Each fan usually consists of two broad lobes, representing areas of greater channel development, which run down the marginal sections of the fan, separated by a central section with less robust development of coarser sediments. The East Rand fan extends for 40 km down the central section from the apex of the fan to the base of the fan where it merges with sediments deposited in the main lacustrine environment. The midfan portion is 50 km wide and the fanbase section 90 km wide.

The western lobe is 45 km long, and the eastern lobe 60 km. In the Welkom fan, the northern lobe is 50 km long, and the eastern lobe 20 km. The East Rand fan is the largest of the six goldfield areas, and the Welkom fan is of intermediate size, the smallest being the Carletonville and Evander fans.

The coarser sediments of the fan exhibit a typical braided stream pattern. The channels are usually filled with the coarsest fraction of the material, but, in some instances, the channel filling is of a finer grain-size than the adjacent sediments. Bars of gravel are well developed in some of the larger channels, while the interfluve areas are composed of finer-grained overbank material. The channels are usually shallow, with a relatively high width:depth channel index. Minter (1972) has reported that the Vaal Reef conglomerate horizon of the Klerksdorp Goldfield is up to two metres thick and covers an area of 250 sq km. Estuarine-like braided channels abound, which are up to 1.5 metres deep and 150 metres wide. Generally, the channels are less than 0.7 metres deep. The largest channels so far recorded occur in the East Rand fan. In the western lobe, two channels have been cut, which are parallel to each other for the greater parts of their lengths, and which have been filled with heavily pyritic sand and only minor amounts of gravel. The one channel has a maximum width of 1 000 metres and a maximum depth of 35 metres, while the other channel is up to 750 metres wide and 85 metres deep. Both channels have been traced for distances of over 8 km in the mine workings.

The arenaceous sediments comprising each fan are typically cross-bedded. Planar, tangential, and trough cross-bedding occur in various parts of the fan, indicating the different energy-levels which prevailed at the time of transportation and deposition of the sand. Sims (1969) and Minter (1972) gathered the data summarized in Table 7, which gives an indication of the thickness of the cross-bedded units and the inclination of the foresets. The units normally vary between 5 and 100 cms in thickness, and the foresets generally dip at between 18° and 25°. The characteristics of the cross-bedding point strongly to a fluvial environment in which the sand was deposited. Distribution of cross-bedding vectors is commonly bimodal, with a large angular difference between the two modes. One of the modes has been interpreted as having been produced by transporting currents moving down the paleoslope and bringing the material from the source-area to, and beyond, the fluvial fans. The second mode is believed to be representative of the distributing currents within the basin, probably longshore drift movement, which washed the sediment parallel to the paleoslope. Sand-waves, with an amplitude of up to one metre, were produced by the distributing currents. These latter currents swept the finer material along the shoreline, giving rise to the asymmetry of the fluvial fans. In all the goldfields, the distributing currents have been observed to have moved in a clockwise direction within the basin.

TABLE 7

THICKNESSES OF CROSS-BEDDED UNITS AND ANGLES OF DIP OF FORESETS

Fluvial Fan	Reef Group	Reef Horizon	Thk	Dip
Welkom	Elsburg	Upper	-	22°
Welkom	Kimberley	A	-	18°
Welkom	Bird	Leader	14	20°
Welkom	Bird	Basal	8	23°
Welkom	Main	Livingstone	24	24°
Klerksdorp	Bird	Vaal	8	18°
Klerksdorp	Bird	Basal Grit	8	23°
West Rand	Klipriviersberg	Ventersdorp	-	19°
West Rand	Main	Livingstone	-	19°

Thk : Average thickness (cm) Dip : Average angle of dip

Each fan is composed of a large number of cycles of sedimentation, with the boundaries between cycles usually represented by unconformities of varying magnitude. The plane of unconformity marked a transition from a transgressive condition, at the end of the preceding cycle, to a regressive process at the beginning of the succeeding cycle. Each cycle started with a coarse phase, frequently gravel or grit, and fined upwards, with numerous breaks in continuity of deposition, reflecting different pulses of sediment inwashing. The basal gravels were formed in interlacing channels and bars, and, laterally, were the least continuous of the beds comprising the cycle. The finer material was distributed in sheets of sand which continued beyond the limits of the fan and intermingled with the offshore lacustrine sediments. The terminal phase of a cycle was generally marked by fine-grained sand, but in several instances the depositional energy dropped low enough to permit the deposition of silts and clays. The end-phase sediments were frequently sub-aerially exposed and scoured by erosional processes that were dominant between the cycles of sedimentation. The planes of inter-cycle unconformity are of considerable economic importance, since all exploitable reefs occur on, or immediately adjacent to, the unconformities.

The evidence points to the cycles building up the fan as being the products of tectonic adjustments along the bounding strike faults which separated the source-area from the depository. The fans, being basin-edge phenomena, often straddled these faults. Relative uplift of the source-area resulted in a regression basinwards of the fanhead environment. The change in the gradient of the paleoslope, brought about by the uplift of the basin-edge, produced a higher energy-level on the fan, and coarser and heavier material was washed in and deposited. A progressive return to a state of equilibrium caused finer and finer sediment to be brought in. Finally, the amount of material being washed in was reduced to a minimum, and the fan was then subjected to optimum winnowing conditions by both the transporting currents down the fan and the longshore currents along the mid-fan and fanbase. Movement along the bounding faults commonly resulted in the fanhead facies of the previous cycle being uplifted and reworked into the basal members of the next cycle.

Minter (1972), from his study of the Vaal Reef in the Klerksdorp Goldfield, has calculated that, at the time of the deposition of the basal gravel, the depth of water on the fan was of the order of 40-50 cm. As the cycle proceeded, the depth of water increased, so that, during the laying down of the finer-grained hangingwall sands, the depth reached between 110 and 120 cm.

Vertical Distribution of Mineralized Horizons

By far the greater proportion of gold and uranium mineralization occurs in, or immediately adjacent to, bands of conglomerate which are preferentially developed at, or near, the base of each cycle of sedimentation. Within the Lower and Upper Witwatersrand Divisions in the Johannesburg area, the conglomerates occupy about 8 per cent of the total thickness of sedimentary strata. On the opposite side of the basin, in the Vredefort area, the conglomerate horizons constitute one per cent of the stratigraphy. Only a small proportion of the conglomerate horizons contains economically exploitable concentrations of gold and uranium, with the maximum number being present in the West Rand fan, where their aggregate thickness amounts to about two per cent of the total thickness of conglomerate development. Over the whole thickness of sediments on the northwestern side of the basin, the exploited conglomerate horizons constitute less than 0.2 per cent.

From Table 8, it can be seen that the main concentration of payable reefs is within the Main-Bird Group of the Upper Witwatersrand Division. The Dominion Group has only one series of reefs, while the Lower Witwatersrand Division has only two series. In the Main-Bird Group of the Upper Witwatersrand Division, there are 9 series of reefs that have been exploited, and in the Kimberley-Elsburg Group 3 series, so that the total number of mineralized horizons which has been worked in the Upper Witwatersrand Division amounts to 12, or 75 per cent of the overall number of exploited horizons within the basin. The Black Reef belongs to the younger Transvaal Sequence, and was formed where the latter sediments onlapped over the gold-bearing Witwatersrand reefs.

The number of reefs that have been mined in a particular fan varies from a minimum of one, in the Evander Goldfield, to a maximum of 10 in the Klerksdorp and West Rand goldfields. The average per fluvial fan is between five and six. In that the areas of fan formation have remained more or less constant on the rim of the basin during the whole of Witwatersrand sedimentation, it can be appreciated how very infrequently, during the infilling of the depository, conditions were favourable for the concentration of the exploitable heavy minerals.

TABLE 8

NUMBER OF MAJOR MINES WHICH HAVE WORKED DIFFERENT REEF HORIZONS IN MAIN FLUVIAL FANS

	WKM	KDP	CTV	WRD	ERD	EVD	Total
Black	-	4	2	4	7	-	17
Ventersdorp	-	1	-	9	-	-	10
Elsburg	1	1	-	3	-	-	5
Kimberley	2	1	-	7	7	4	21
Bird	12	7	-	7	-	-	26
Livingstone	-	-	-	2	4	-	6
Johnstone	-	-	-	1	3	-	4
South	-	1	-	9	3	-	13
M.R. Leader	-	-	-	-	37	-	37
Pyritic Quartzites	-	-	-	-	10	-	10
Main	-	1	-	12	7	-	20
North	-	-	-	1	3	-	4
Carbon Leader	-	-	5	-	-	-	5
Jeppestown	-	2	-	-	-	-	2
Government	-	4	-	-	-	-	4
Dominion	-	2	-	-	-	-	2

WKM : Welkom Fluvial Fan
KDP : Klerksdorp Fluvial Fan
CTV : Carletonville Fluvial Fan
WRD : West Rand Fluvial Fan
ERD : East Rand Fluvial Fan
EVD : Evander Fluvial Fan

An approximate guide can be gained to the relative economic importance of each reef through the number of mines which have exploited it. Figure 9 is a representation of the frequency of mining on each mineralized horizon. The size of the different mines is highly variable; therefore, the number of mines is not directly proportional to the quantity of gold and/or uranium that has been extracted. The Carbon Leader, worked on five very large, deep-level mines, has contributed appreciably greater amounts of gold than the Black Reef which has been mined on 17 much smaller, shallow-level mines. Nevertheless, it is apparent that there are six peaks among the mineralized horizons of the Witwatersrand Sequence - the Government Reefs of the Klerksdorp fan, the Carbon Leader (Main-Bird Group) of the Carletonville fan, the Main Reef (Main-Bird Group), of the West Rand and East Rand fans, the Main Reef Leader (Main-Bird Group) of the East Rand fan, the Bird Reefs (Main-Bird Group) of the Welkom, Klerksdorp, and West Rand fans, and the Ventersdorp Contact Reef (Kimberley-Elsburg Group) of the West Rand fan. The smoothed profile indicates that there is a comparatively rapid build-up in economic importance from the Dominion Reef to the Main Reef Leader, and then a much slower decrease in importance from the latter reef to the Black Reef. Conditions favourable to the deposition of gold reached their acme in Main Reef Leader times, and this mineralized horizon represents the pivotal point in the stratigraphic distribution of mineral wealth in the Witwatersrand Basin.

The stratigraphic distances between the reef horizons above the Main Reef Leader are much smaller than those between the reefs lying above the base of the Witwatersrand Sequence and below the Main Reef Leader. The more closely spaced development of reefs in the Upper Witwatersrand Division was probably the result of more frequent tectonic adjustment and more intense reworking of

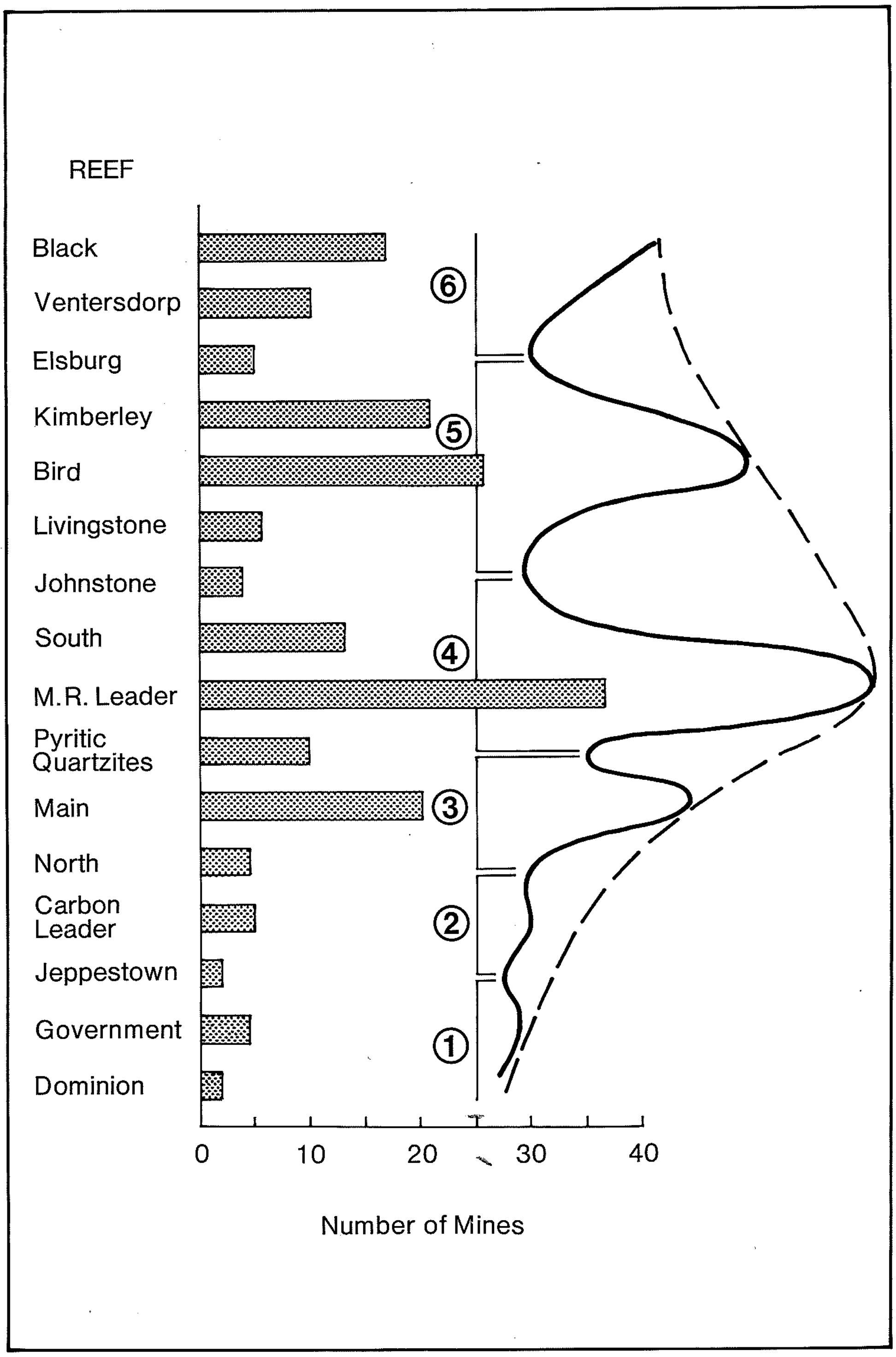


Figure 9 : *The relative importance of the 16 different stratigraphic horizons in which economic gold and uranium mineralization occurs, as indicated by the number of mines which have exploited each horizon. The representation is purely diagrammatic, since there is great variation in the sizes of the individual mines. The Main Reef Leader is the most important economic horizon. Of the 16 reefs, 12 are members of the Upper Witwatersrand Division, emphasizing the stratigraphic centre of gravity of the gold and uranium mineralization.*

previously deposited material, which processes followed after the basin started shrinking early in Main-Bird times. The gold in the apices and upper midfan sections of the Main Reef, Main Reef Leader, and South Reef was probably recycled a number of times before the last reef horizon was formed in Black Reef times.

The overall regressive nature of sedimentation in the Upper Witwatersrand Division is reflected in the progressively greater thickness of the conglomerate groups stratigraphically upwards. In Table 9 are shown the variations in the zone thicknesses over which the bands of conglomerates are concentrated. In the normal geometry of a fluvial fan, more gravels are deposited in the fanhead and upper midfan sections, while lesser quantities of pebbles, of small size, are transported to the fanbase section. The thicknesses on Table 9, plus other sedimentological features, indicate that the North-Main, the Leader-South, and the Bird groups of conglomerates were formed in lower midfan environments, the Kimberley series of reefs in upper midfan sections, and the Elsburg conglomerates in fanhead environments. This continuous superimposition of more proximal facies over more distal facies is indicative of a shrinking basin, with a progressive advance of the apices of younger fans from the basin-edge towards the depositional axis. Comparing Table 9 with Table 8 and Figure 9 reveals that optimum conditions for the concentration of heavy minerals in the conglomerates prevailed in the lower midfan environments. The hydraulic regime became less and less favourable for the deposition of detrital particles, as the fanhead and the fanbase were approached from the midfan sections.

TABLE 9

THICKNESS OF UPPER WITWATERSRAND REEF GROUPS
AT JOHANNESBURG

Reef Group	Thickness (metres)
Elsburg	400
Kimberley	210
Bird	70
Leader-South	40
North-Main	30

THE NATURE OF THE MINERALIZATION

Production of Gold and Uranium

The amount of gold won from mining operations in the Witwatersrand Basin between 1887 and 1972 is shown in Table 10. This is a minimum figure, since early production figures are not necessarily complete. From 112 mines that have been operative at one time or another, almost 3 billion metric tons of ore have been extracted. From this ore, 28 722 metric tons of gold have been won. The average grade of the ore treated has been a little over 10 ppm gold, with a range per goldfield of 7 to 21 ppm. The relative contributions of each goldfield have been summarized in Table 11. The East Rand fluvial fan, in addition to being the oldest producer, has also been the main contributor of tonnage and gold, but at the expense of having the second lowest average yield per ton. The Carletonville Goldfield has proved twice as rich as the average for the basin as a whole. The second richest field is the Welkom group of mines, while the lowest yields have come from the West Rand Goldfield.

Uranium was first recovered in 1953 from the same ores as have yielded the gold. In the 20 years of production till the end of 1972, approximately, 76 012 metric tons of uranium oxide were won from 271 million tons of rock, at an average recovery grade of 280 ppm. The yield of uranium oxide is thus 28 times that of gold, and, by weight, uranium is a more important

TABLE 10

GOLD PRODUCTION FROM THE WITWATERSRAND GOLDFIELDS : 1887-1972

Goldfield	Year of First Production	Total Number of Mines	Ore Treated millions tons	Gold Recovered kilograms	Average Grade gm/ton
Welkom	1951	14	302.447	4 659 557	15.41
Klerksdorp	1941	7	172.818	2 299 301	13.30
Carletonville	1942	5	123.012	2 632 255	21.40
West Rand	1888	20	451.150	3 121 803	6.92
East Rand	1887	62	1 737.680	15 412 216	8.87
Evander	1958	4	53.032	597 219	11.26
TOTAL	1887	112	2 840.139	28 722 351	10.11
Total Sales Value of Witwatersrand Gold : 1887-1972 - $33 896 713 000					

TABLE 11

GOLD PRODUCTION FROM THE WITWATERSRAND GOLDFIELDS : 1887-1972

Goldfield	Percentage of Total Tonnage	Percentage of Total Gold	Years in Production	Ratio of Grade to Mean Grade
Welkom	10.65	16.22	22	1.52
Klerksdorp	6.08	8.02	32	1.32
Carletonville	4.34	9.16	31	2.17
West Rand	15.88	10.87	85	0.68
East Rand	61.18	53.64	86	0.88
Evander	1.87	2.09	15	1.11
	100	100	86	1.00

constituent of the ore than gold, but not by value. Table 12 shows that the West Rand Goldfield, which has the lowest yield per ton of gold, has, by far, the richest ores of uranium. This inverse relationship does not apply to the rest of the fields, and there is no general correlation between gold and uranium values. The lowest average recovery grade has been recorded in the Welkom Goldfield, but no uranium at all has been won from the Evander mines.

A comparison of Table 12, Table 8, and Figure 9 reveals that maximum gold concentration occurs at a different stratigraphic position than does the richest uranium mineralization. The most significant gold reefs occur in the lower (or Main) section of the Main-Bird Group, while the more important uranium horizons are located in the upper (or Bird) section of the same group. The richest carriers of both gold and uranium are the Carbon Leader (Main strata) of the Carletonville Goldfield and the Basal and Vaal reefs (both in the Bird strata) of the Welkom and Klerksdorp fields, respectively. The Dominion Reef is generally richer in uranium than in gold, as are the Bird reefs over much of their area of development. Whiteside (1970a) has reported that the horizons between,

TABLE 12

PRODUCTION OF URANIUM OXIDE FROM WITWATERSRAND BASIN
1953-1972

Reef	Goldfield	No. of Producers	U_3O_8 (kilograms)	U_3O_8 gms/ton
Elsburg	Welkom	1	328 533	117
Kimberley	East Rand	2	3 005 335	205
Bird	Welkom	7	12 909 704	196
Bird	Klerksdorp	6	29 558 598	258
Bird	West Rand	4	21 761 004	628
Main	Klerksdorp	2	561 273	154
Carbon Leader	Carletonville	4	9 204 809	248
Jeppestown	Klerksdorp	2	690 310	274
Dominion	Klerksdorp	1	1 882 841	510
All	Welkom	8	13 238 237	193
All	Klerksdorp	11	32 633 022	262
All	Carletonville	4	9 204 809	248
All	West Rand	4	21 761 004	628
All	East Rand	2	3 005 335	205
All	Evander	0	-	-
All	All	29	76 011 992	280

and including, the North and South reefs contain no economic concentrations of uranium, except to a very limited extent in a small area of the Klerksdorp field. The conglomerates at the very top of the succession - the Elsburg Reefs and the Ventersdorp Contact Reef - are also poor in uranium. The Black Reef of the Transvaal Sequence does not carry significant amounts of uranium.

Types of Reefs

The conglomerates have long been regarded as the typical gold- and uranium-bearing horizons of the Witwatersrand Basin. It is certainly true that most of the gold and uranium so far won has come from the conglomerates, but other types of mineralization have become progressively more important as newer goldfields have been opened up. It has also become apparent that, in many cases, the gold and uranium in the matrix of the conglomerates were not deposited at the same time as the original gravels were laid down. This does not imply an epigenetic origin for the mineralization, as was put forward in the hydrothermal theory, favoured by a minority of earlier investigators. It means that the gold was incorporated into the conglomerate by the reworking of previously deposited sediments, or was introduced into the gravels during the washing over of later sands. The gold and uranium now exploited occur in five forms :

(i) in the matrix of conglomerates;

(ii) in heavily pyritic sands which usually fill erosion channels, the gold, uranium, and pyrite particles lying on the foresets of the cross-bedded sands;

(iii) on sand along the planes of unconformity that separate two cycles of sedimentation;

(iv) on mud along the planes of unconformity that separate succeeding cycles of sedimentation; and

(v) in carbon seams that are developed on, or immediately adjacent to, planes of unconformity.

In the ideal case, where the full spectrum of reefs is present, types (iii), (iv), and (v) would be the result of processes active during the terminal phase of a preceding cycle of sedimentation, and types (i) and (ii) the responses in the initial stage of the succeeding cycle. Depending upon the degree of turbulence and the prevailing depositional energy-level at the beginning of the succeeding cycle, the heavy minerals deposited at the end of the preceding cycle either would be buried, undisturbed, beneath the later sands, or be picked up and incorporated into the matrix of the overlying gravels.

In that coarser material, frequently in the form of conglomerates, marks the beginning of many of the cycles in the Upper Witwatersrand Division, gold and uranium, whether belonging to the preceding or the succeeding cycle, are closely associated with conglomerate horizons. The conglomerates are the main exploration targets, even where the gold is located a short distance below, on the unconformity which marks the end of the earlier cycle of sedimentation. In a number of instances, the energy-level of the succeeding cycle was not high enough to bring in gravels, and only sand and silt washed over the unconformity, so that mineralized bands can occur along the interface between sand and sand or mud and sand, without any conglomerate being present in the immediate vicinity.

The carbon seams that have considerable economic importance on the horizons of the Carbon Leader of the Carletonville Goldfield, the Vaal Reef of the Klerksdorp Goldfield, and the Basal Reef of the Welkom Goldfield, but which also assume local importance elsewhere in the stratigraphy, would now appear to be the remains of very primitive plant-life. In its present form, the carbon is either thucholite, a mixture of hydrocarbon and uraninite, with varying amounts of gold and sulphides, or a substance resembling bituminous coal. Many interpretations have been put forward for the origin of this material, the most strongly argued of the earlier ideas being that it represented the product of polymerization of methane gas by radioactive minerals in the sediments. The most recent work by Hallbauer (1972) presents persuasive evidence that the carbon was originally blue-green filamentous algae, with a suggestion that material resembling fungal spores might also be present. It would seem that the plant remains are part of old algal mats that developed in quiet-water conditions on the margins of the fluvial fans or along the fanbase sections, at the end of certain cycles of deposition. Depending upon the coarseness of the sediments of the succeeding cycle, the carbon can be preserved intact, in which case it forms the carbon-seam type of reef, or it can be broken up and then mixed with the succeeding material, in which it takes the form of small particles, called fly-speck carbon, 0.5-1.0 mm in diameter, often clustered as three or more pieces.

Hallbauer and Joughin (1972) have reported that 85 per cent of the gold recovered from the Witwatersrand mines comes from reefs less than one metre thick, and that a very large fraction of this amount occurs in reefs less than 0.1 metre thick. Over strike and dip sections of the reefs, the gold is patchily distributed in zones of general enrichment or impoverishment, which run for distances from a few tens of centimetres up to a few metres. These patches have a typical dimension of about one metre. The gold particles themselves are distributed according to five different patterns within the reefs, none of the patterns being consistent over large areas (Hallbauer, 1972) :

(i) particles which are dispersed throughout the matrix of the reef, in a somewhat even manner, with the individual particles spaced a few millimetres apart;

(ii) discrete particles separated from each other by distances of up to 100 mm;

(iii) isolated clusters, very rich in gold particles, inside a few cubic centimetres of matrix - 200 grains of gold might be present in a patch measuring 0.4 x 0.7 mm;

(iv) thin streaks on either the hangingwall or the footwall contact; and

(v) very rich, isolated clusters occupying a few cubic centimetres and spaced 50 mm or more apart.

In many of the reefs, there is a very marked concentration of gold on the bottom contact. Minter (1972) found that, in the Vaal Reef of the Klerksdorp field, the average grade over the whole thickness of the reef was of the order of 15 ppm, but that concentrations of up to 1 500 ppm on the basal contact were not rare. In the past, it was assumed that the basal concentration indicated gravity settling of heavy minerals to the bottom of the gravel bed. Where the reef was originally an openwork gravel, over and into which sand washed during a succeeding pulse of sedimentation, this mechanism might well have been operative. However, in reefs which have a less well-developed conglomerate, it is now thought that the gold was concentrated on the top of the previous cycle, with the later pebbles being deposited on a very thin layer of precious metal. The supposed basal enrichment would then represent concentration by winnowing during the terminal stages of the preceding cycle, and not concentration by gravity settling of heavy detrital particles during the early stages of the succeeding cycle. In such cases, the key to the distribution patterns of gold mineralization lies in the sedimentology of the end-phase of one cycle of sedimentation and, to a much lesser extent, in the processes active in the initial phases of the next cycle.

The gold in the carbon seams occurs either as very small, discrete particles on top of, or within, the seams or as coatings and replacements of the algal filaments. The particles are believed to be of detrital origin, representing micro-nuggets that were physically entrapped in the network of filaments. The coatings and replacements probably formed from gold in solution. It is possible that, in the primitive, anoxygenic atmosphere that prevailed at the time the Witwatersrand deposits formed, gold could have been dissolved in cyanide- or chlorine-rich solutions. The algae, reacting with the mineralized waters in which they developed, absorbed the gold from solution, to build up protective coatings round the filaments or to replace the fibres. It is also possible that streaks of gold were already present on the sandy or muddy surface that formed during the terminal stages of a cycle of sedimentation, and that the algae grew subsequently on the gold-streaked unconformity, the base of the algal mats being anchored in the gold and other heavy minerals. By direct contact, without any intervening stage of solution, the gold could have been absorbed into the plant structure.

In the Klerksdorp Goldfield, at least, the gold:uranium ratio is greater in the conglomerates than in the carbon seams (Minter, 1972). In general, the maximum concentrations of uranium are more towards the depositional axis of the basin than are the greater enrichments of gold. In any one particular horizon on a fan, the reef tends to have a higher gold tenor relatively closer to the fanhead and a greater uranium grade relatively closer to the fanbase.

Composition of Conglomerates

A normal conglomerate consists of 80 per cent, by weight, of pebbles, set in a matrix composed of recrystallized quartz, a phyllosilicate mixture of sericite, chlorite, and sometimes pyrophyllite, and sulphides and heavy minerals (Liebenberg, 1973). In addition to the presence of pebbles, the conglomerate is generally distinguishable from overlying and underlying quartzites by its cleaner nature, a larger percentage of phyllosilicates having been removed than from the adjacent sands. The quartz pebbles are barren. Only infrequent veinlets and dust-like inclusions of sulphides, gold, and hydrocarbon might be present in them, the products of remobilization after the deposition of the pebbles. The hangingwall and footwall quartzites typically consist of a mosaic of quartz grains, with lesser amounts of fine-grained micaceous constituents, and still smaller amounts of chromite, zircon, and pyrite. Gold and uranium normally do not occur in the matrix of the ordinary type of quartzite. An example of the difference between the matrix of a conglomerate horizon and the overlying quartzites can be seen in Table 13, taken from Minter (1972).

TABLE 13

PERCENTAGE MINERAL COMPOSITION OF CONGLOMERATE AND QUARTZITE IN KLERKSDORP FLUVIAL FAN

Mineral	Vaal Reef Matrix	MB.4 Quartzite
quartz	95	62
rock fragments	1	4
sericite	3	26
chlorite	1	8

The types of pebbles which can be found in the conglomerates are listed in Table 14, which was prepared from observations made by Sims (1969) in a number of different reefs in the Main-

TABLE 14

COMPOSITION OF PEBBLES IN UPPER WITWATERSRAND STRATA
IN WELKOM FLUVIAL FAN

Durable Pebbles	Non-Durable Pebbles
white quartz	yellow silicified shale
smoky quartz	grey silicified shale
opalescent blue quartz	grey quartzite
dark grey massive chert	yellow quartzite
grey banded chert	green quartzite
green banded chert	quartz porphyry
red banded chert	serpentinite
	talc schist
	chlorite schist

Bird and Kimberley-Elsburg groups in the central part of the Welkom fluvial fan. The relative percentages of some of these pebble-types are set out in Table 15 (after McKinney, 1964).

TABLE 15

VARIATIONS IN COMPOSITION AND SIZE OF PEBBLES IN DIFFERENT REEFS
IN WESTERN HOLDINGS MINE, WELKOM FLUVIAL FAN

Pebbles	1	2	3	4	5	6
quartz - %	3	50	45	47	10	10
green chert - %	5	0	0	0	60	50
yellow chert - %	85	2	14	40	11	10
black chert - %	2	46	32	5	15	20
quartzite - %	5	2	7	3	1	5
quartz porphyry - %	0	0	2	5	3	5
quartz - mm	30	30	15	135	210	150
green chert - mm	15	-	-	-	90	50
yellow chert - mm	40	-	10	75	15	40
black chert - mm	15	15	15	10	25	75
quartzite - mm	40	-	10	10	-	150
quartz porphyry - mm	-	-	-	100	150	135

1. UF-2 Reef, Livingstone Group
2. Middle Reef, Bird Group
3. Leader Reef, Bird Group
4. B Reef, Kimberley Group
5. Lower Reef, Elsburg Group
6. Upper Reef, Elsburg Group

It can be seen that the pebble assemblages vary widely from reef to reef, and in a number of instances the particular reef horizon can be accurately identified from the composition of the contained pebbles.

The lithology of the pebble frequently determines its mean size. The average diameters of pebbles vary between reefs, as can be seen in Table 15, where the pebbles of the Kimberley-Elsburg Group are appreciably greater in size than those of the underlying Main-Bird Group. Larger pebbles are normally indicative of a higher-energy regime that typically prevails in the fanhead and upper midfan sections of the depository. In that gold and uranium are generally concentrated in the midfan section, it is often, but not necessarily, the case that lower concentrations of the two are found where larger-pebble conglomerates are developed. In addition to the size of the pebbles decreasing down the fluvial fan into the lacustrine environment, the ratio of durable to non-durable pebbles increases substantially. Sims (1969) observed that, in the Welkom fan, the percentage of non-durable pebbles in the B Reef diminishes from 77 to 34 per cent from the upper midfan to the lower midfan sections, and, in the Big Pebble Reef, from 27 to 9 per cent. In general, where a conglomerate is characterized by a high proportion of non-durable pebbles, the gold and uranium values are low.

Table 16 gives an indication of the pebbles which are present in various conglomerates of the Klerksdorp fan (Minter, 1972). The highest percentage of quartz and the lowest percentage of quartzite pebbles are present in the Vaal Reef, a feature which is usually observed in conglomerates with economic concentrations of gold. The mean pebble-size of the Vaal Reef is 22 mm and the mean grain-size of quartz in the matrix 0.54 mm. The Trask sorting coefficient of the pebbles in the Vaal Reef is 1.29-1.34, and they could be regarded as being part of well-sorted marine gravels, if it were assumed that they had gone through one cycle of sorting only. The pebbles are roller- or muffin-shaped, and have a high degree of rounding. Modified dreikanter pebbles have been found, indicating fluvial reworking of pebbles abraded by wind in the source-area. The pebbles constitute 20 per cent of the volume of the Vaal Reef, which low figure would suggest that this reef is not a typical conglomerate.

TABLE 16

AVERAGE SIZE AND COMPOSITION OF PEBBLES IN MAIN-BIRD STRATA
OF KLERKSDORP FLUVIAL FAN

Pebbles	Basal Grit	Vaal Reef	Zandpan Marker	Upper MB.4 Grit
Average size (mm)	-	22	30	30
Quartz (%)	70	85	78	52
Chert (%)	17	12	13	8
Quartzite (%)	7	3	5	10
Quartz porphyry (%)	6	<1	4	21
Yellow shale (%)	<1	<1	<1	-
Black shale (%)	-	<1	<1	-
Chloritic schist (%)	<1	<1	-	9
Serpentinite (%)	<1	-	<1	-

Whereas the gold has a tendency to be concentrated near the base of a conglomerate band, uranium can occur throughout the thickness of the horizon. From this it follows that thicker reefs often have greater concentrations of uranium. Table 17 has been compiled from Minter's (1972) data to show that, if uranium mineralization is present, the uranium:gold ratio is considerably enhanced where thicker reefs are developed. Uranium is not a characteristic feature of the Main group of reefs anywhere in the basin, and there is no apparent relationship between reef thickness and gold:uranium ratios. However, in the Bird reefs, which are the best uranium carriers in the stratigraphic column, there is a clear indication that much more uranium is present where the reef is thicker.

Thick conglomerates are not the product of one single pulse of sedimentation. They are normally built up of three or four inwashings of gravel, with intervening periods of sand

TABLE 17

THICKNESSES, COMPOSITIONS, AND URANIUM/GOLD RATIOS OF SELECTED REEF HORIZONS

Reef Group	Reef Horizon	Fluvian Fan	TN	SZ	QU	CT	QT	OS	U/Au
Bird	Zone 2	West Rand	62	21	77	7	16	-	769
Bird	Monarch	West Rand	99	18	82	6	11	-	435
Bird	White	West Rand	35	12	85	8	3	4	40
Bird	Vaal	Klerksdorp	15	22	85	12	3	-	11
Bird	Basal	Welkom	36	20	60	23	5	12	18
Main	Livingstone	West Rand	50	35	-	-	-	-	11
Main	South	West Rand	10	17	86	7	7	-	14
Main	Main	West Rand	110	37	84	6	10	-	9
Main	North	West Rand	50	30	83	6	11	-	-

TN : Average thickness (cm)

SZ : Average size of 10 largest pebbles (mm)

QU : Percentage vein quartz pebbles

CT : Percentage chert pebbles

QT : Percentage quartzite pebbles

OS : Percentage other types of pebbles

U/Au : Ratio of uranium content to gold content

deposition. Heavy minerals, even if they do tend to form basal concentrations, can therefore occur in several bands through the total thickness of conglomerate, each band being at the bottom of an individual pulse of gravel.

Mineralogy of the Reefs

Table 18 has been prepared to show the full range of minerals that have so far been observed in the various types of gold- and uranium-bearing reefs within the Witwatersrand Basin. The economic minerals are those that have been commercially exploited - the ores of gold, platinum, and uranium, and pyrite which has been used in the manufacture of sulphuric acid. The list contains primary, secondary, and even some tertiary minerals, the latter two groups of which are the products of the metamorphism and remobilization which have affected the mineralized horizons. The fact that the economic minerals and the sulphides have been reconstituted, for the most part, has given rise in the past to the arguments in favour of the mineralization being of epigenetic origin. Although remobilization did not cause the secondary products to move more than a few millimetres from the primary sources, the change in morphology of many of the minerals gives the appearance of crystallization *in situ* and of a hydrothermal sequence of replacement - the evidence used by the hydrothermalists in their dispute with the placerists.

The bulk of the gold occurs in the free state, and only a small portion is locked in the sulphides. Hallbauer and Joughin (1973) stated that the gold occurs in three forms : with quartz or silicates; with thucholite; or as a coating on pyrite. Liebenberg (1973) found that most of the gold is confined to the matrix of the conglomerates, where it is associated with quartz, chlorite, and sericite, and only rarely with muscovite, chloritoid, tourmaline, zircon, or iridosmine. Sometimes, the gold is associated with chromite. The gold frequently is present in cracks and pits in uraninite grains, these stringers of gold varying in width between 0.005 and 0.25 mm. Secondary sulphides, such as galena, pyrrhotite, chalcopyrite, pentlandite, and sphalerite, often accompany the gold when it is in the uraninite.

TABLE 18

MINERALS PRESENT IN WITWATERSRAND AURIFEROUS HORIZONS

Economic Minerals	Sulphides	Oxides	Silicates	Others
gold	pyrrhotite	quartz	muscovite	calcite
tellurium	leucopyrite		sericite	dolomite
	loellingite	cassiterite	pyrophyllite	
silver	marcasite		chlorite	xenotime
stromeyerite		chromite	chloritoid	monazite
proustite	chalcopyrite		biotite	
dyscrasite	chalcopyrrhotite	columbite		diamond
	cubanite		kaolinite	graphite
platinum	chalcocite	corundum		
platiniridium	neodigenite		epidote	
osmiridium	covellite	magnetite		
iridosmine	bornite	hematite	tourmaline	
sperrylite	tennantite	goethite		
braggite			garnet	
cooperite	galena	rutile		
		leucoxene	zircon	
uraninite	sphalerite	ilmeno-rutile		
thucholite		ilmenite	sphene	
brannerite	molybdenite	anatase		
uranothorite		brookite		
	bismuthinite			
pyrite				
	arsenopyrite			
	skutterudite			
	cobaltite			
	glaucodot			
	linnaeite			
	safflorite			
	gersdorffite			
	niccolite			
	millerite			
	pentlandite			
	bravoite			
	mackinawite			

The gold that is found with thucholite, in addition to encrusting or replacing the algal filaments, takes the form of veinlets, specks, and patches in phyllosilicates that are wedged in cracks and cavities in the columnar thucholite (Liebenberg, 1973). Such gold has a thickness of 0.001-0.03 mm. Associated with the thucholite may be pyrite, pyrrhotite, chalcopyrite, pentlandite, sphalerite, cobaltite, linnaeite, galena, arsenopyrite, all of which may be replaced by gold. According to Hallbauer (1972), the columns, 0.2 mm in diameter and 0.5-1.0 mm long, of the columnar carbon or thucholite, consist of a tissue-like outer shell with a distinctly fibrous structure in longitudinal section. Inside the columns is a network of irregular fibres, individuals of which have a diameter of about one micron. Gold occurs in a fibre-like form between the columns and parallel to the long axis, or as a replacement or encrustation on the network of filaments within the columns.

Only a few pyrite grains contain included gold, but the precious metal is often present in particles of pyrrhotite, chalcopyrite, galena, pentlandite, sphalerite, arsenopyrite, linnaeite, and cobaltite (Liebenberg, 1973). Gold in the banded pyritic quartzites replaces pyrite, pyrrhotite, sphalerite, chalcopyrite, arsenopyrite, quartz, chlorite, and sericite. In such reefs, most of the gold is a replacement of buckshot pyrite which has a diameter of 0.002-0.18 mm. Gold in the Dominion Reef is relatively rare, and, when it does occur, it has a preferential association with leucoxene, and replaces pyrite, chlorite, and quartz. In the Ventersdorp Contact Reef, gold replaces quartz and chlorite, and, to a lesser extent, chalcopyrite and pyrite. In this reef, pyrrhotite is a very common associate of gold. In the Black Reef, gold replaces quartz. Much of the metal is associated with pyrite, and where other sulphides are present, the gold has a greater affinity for sphalerite than for chalcopyrite or pyrrhotite (Liebenberg, 1973).

The platinoids are present in only very low concentrations in the reefs. Cousins (1973) has stated that 3.5 milligrams of platinoids per ton has been the average recovery grade in the basin. One part of the platinum group of metals has been won for every 2 000 parts of gold.

In the typical conglomerate, pyrite forms 3 per cent of the total reef, and about 15 per cent of the matrix alone. Pyrite constitutes about 90 per cent of the sulphides present (Saager and Esselaar, 1969). It occurs predominantly as rounded, waterworn, detrital grains which are accompanied by pyrite pseudomorphs, concretions, and subhedral crystals. Secondary pyrite forms either fracture fillings in other components of the matrix or overgrowths on older detrital pyrite. Of the other sulphides present, only cobaltite, linnaeite, and arsenopyrite have morphologies that are indicative of detrital, water-transported materials. The heaviest concentrations of pyrite are in the banded pyritic quartzites, where this sulphide can comprise 25 per cent of the total rock. The pyrite grains are in hydraulic equilibrium with unequivocal detrital particles, and generally rest on the foresets of cross-bedded units. Sedimentary partings, representing breaks in sedimentation, are very frequently layered with pyrite.

The quantitative mineralogy of two different types of reefs is shown in Table 19, compiled from data provided by Liebenberg (1973). Despite the fact that the two reefs were formed in different environments, the Vaal Reef being a lower midfan development, and the Ventersdorp Contact Reef an upper midfan to fanhead sediment, the mineralogical composition shows significant differences only in the contents of chlorite, sericite, and sulphides. The higher chlorite content of the Ventersdorp Contact Reef has been produced, in part, by the fact that the reef shows an intermingling with volcanic material that was laid down at the base of the immediately overlying Klipriviersberg Group.

TABLE 19

MINERALOGICAL COMPOSITION OF TWO AURIFEROUS CONGLOMERATES

Component	Vaal	Ventersdorp
gold - ppm	50	44
silver - ppm	8	5
uranium oxide - ppm	870	290
quartz - %	88.3	88.9
chlorite - %	0.8	4.9
muscovite (sericite) - %	4.4	3.0
pyrophyllite - %	0.1	0.2
zircon - %	0.1	0.2
chromite - %	0.2	0.1
titanium minerals - %	0.1	0.1
sulphide minerals - %	6.0	2.6

Vaal : Vaal Reef, Hartebeestfontein Mine, Klerksdorp Fluvial Fan

Ventersdorp : Ventersdorp Contact Reef, Venterspost Mine, West Rand Fluvial Fan

The three most persistent and abundant heavy minerals in the matrix of the conglomerate are chromite, zircon, and leucoxene, the last-mentioned being a secondary alteration product of primary titanium minerals. The relative percentages of these three minerals in the succession of reefs is depicted in Table 20, which represents a summation of data taken from Coetzee (1966). The relative percentages vary widely from reef to reef, and many of the mineralized horizons can be distinguished one from the other on triangular plots of these heavy mineral assemblages. The origin of the titanium minerals could be either in basic or acid igneous rocks, with the result that leucoxene cannot be reliably employed to gain an idea of the source-rocks that were supplying the depository at the time that any one particular reef was being laid down. However, it can be taken that the chromite would be preferentially drawn from ultrabasic to possibly basic rocks, while the zircon would come from acid rocks. The chromite:zircon ratio is, therefore, some measure of the mix of material being eroded in the source-area.

TABLE 20

RELATIVE PERCENTAGES OF CHROMITE, ZIRCON, AND LEUCOXENE
IN MAJOR WITWATERSRAND REEFS

Reef Horizon	Chromite	Zircon	Leucoxene	Chromite/Zircon
Black	58	14	28	4.14
Ventersdorp	34	25	41	1.36
Elsburg	64	34	2	1.88
Kimberley	59	26	15	2.27
Bird	38	36	26	1.06
South	6	7	87	0.86
Leader	11	12	77	0.92
Main	14	8	78	1.75
Carbon Leader	34	39	27	0.87
Dominion	13	9	78	1.44

In reefs which are sufficiently close to each other stratigraphically to be considered as belonging to one major and relatively continuous episode of sedimentation, such as the Main-Leader-South and the Kimberley-Elsburg-Ventersdorp group, it would appear that the chromite: zircon ratio decreases upwards. An increase in chromite heralds the onset of a major episode of sedimentation. From this it can be concluded that first-order tectonic adjustment in the source-area exposed more ultramafic material for erosion, and that, as conditions tended towards a state of equilibrium, less and less ultramafic rocks were available, and more and more acidic rocks provided the erosional debris. In Table 20, the times of relatively greater exposure of ultramafic rocks in the source-area are indicated at the Dominion, Main, Bird, Kimberley, and Black horizons.

Chemistry of the Reefs

A succession of reefs lying stratigraphically one above the other in the Upper Witwatersrand Division on the West Rand Consolidated Mine in the West Rand fluvial fan was analyzed to produce the results depicted in Table 21. It is apparent that the chemistry very closely reflects the mineralogy, with quartz and phyllosilicates being responsible for the very high silica content. The figures support Fuller's (1958) contention that higher silica is a characteristic of the rocks in the Main Reef group, in that the Main Reef and the South Reef have silica contents in excess of 93 per cent. The silica content of the conglomerates is greater than 86 per cent in all cases, whereas silica drops to below 63 per cent in the banded pyritic quartzites, illustrating a point that has been mentioned previously to the effect that the phyllosilicate content of the adjacent quartzites is always higher than that of the enclosed conglomerates, and that the coarser clastics are cleaner than the finer sands. The appreciably higher pyrite content of the banded pyritic quartzites is also readily apparent.

TABLE 21

CHEMICAL ANALYSES OF AURIFEROUS CONGLOMERATES IN THE WEST RAND CONSOLIDATED MINE, WEST RAND FLUVIAL FAN

	NR	MR	BPQ	SR	LLR	ULR	WR	BR
SiO_2	89.26	93.14	62.08	94.06	86.38	88.18	87.19	88.32
Al_2O_3	2.31	1.69	1.92	2.51	5.13	4.42	3.97	1.77
Fe_2O_3	1.01	0.48	10.72	0.30	1.63	1.03	1.11	3.01
FeO	3.05	1.36	2.07	0.79	0.78	1.07	0.87	0.79
FeS_2	1.26	1.24	14.88	0.73	1.98	1.72	1.16	3.60
MgO	0.45	<0.02	1.07	<0.02	<0.02	<0.02	0.05	<0.02
CaO	<0.02	<0.02	<0.02	<0.02	0.03	<0.02	0.02	<0.02
Na_2O	0.04	0.03	0.02	0.10	0.61	0.12	0.04	0.10
K_2O	0.01	0.02	0.01	0.12	0.35	0.14	0.27	0.18
TiO_2	0.10	0.12	0.25	0.15	0.53	0.28	0.22	0.09
P_2O_5	0.03	0.04	0.02	0.03	0.03	0.02	0.04	0.02
MnO	0.02	0.01	0.03	0.02	0.02	0.01	0.02	0.01
Loss	1.43	1.07	6.36	0.99	1.91	2.15	2.15	2.27
Th*	<5	223	12	15	14	23	228	8
La*	5	38	18	8	38	23	26	15
Cl*	137	179	67	78	124	83	84	56
Total	98.98	99.24	99.44	99.81	99.40	99.15	97.14	99.17

Loss : corrected loss on ignition
* : ppm
BR : Boulder Reef
WR : White Reef
ULR : Livingstone Reef (Upper Band)
LLR : Livingstone Reef (Lower Band)
SR : South Reef
BPQ : Banded Pyritic Quartzites
MR : Main Reef
NR : North Reef

Some trace elements are shown in Table 21, but more comprehensive studies have been carried out by Sellschop, Rasmussen, and Fesq (1973) and by Rasmussen and Fesq (1973). The results of their analyses are summarized in Table 22 and Table 23, respectively. There are distinct differences between the trace element patterns for shales and quartzites, but it would appear from Table 23 that, in the case of the Kimberley Reefs of the West Rand fan, at least, the matrix of the conglomerates is not readily distinguishable chemically from the overlying and underlying quartzites. This probably reflects the fact that much of the sand which infiltrated into the openwork gravels was associated with the series of pulses which brought large quantities of finer arenaceous material into the basin during the intermediate stages of the cycle of sedimentation, after the initial high-energy phase that deposited the pebbles, and before the terminal phase which transported the very fine sands, silts, or muds.

The carbon seams, identified as the remains of plant colonies, have given the analytical results shown in Table 24 (de Kock, 1964). From the relative percentages of the organic components, the carbon could be classified as a bituminous coal. The sulphur content is influenced to a great

TABLE 22

TRACE ELEMENT CONTENT OF WITWATERSRAND STRATA IN THE EAST RAND PROPRIETARY MINE, EAST RAND FLUVIAL FAN

	Na %	Sc ppm	Co ppm	Rb ppm	Cs ppm	Ba ppm	La ppm	Ce ppm	Eu ppm	Yb ppm	Lu ppm	Hf ppm	Ta ppm
Kimberley Shale	0.14	26.53	59.00	117	2.88	719	8.20	53.60	1.23	0.94	0.13	1.90	-
Bird Quartzite	0.03	3.10	6.00	-	0.66	-	6.93	25.70	0.56	0.42	0.05	1.34	0.26
Livingstone Quartzite	0.02	6.56	10.80	-	-	-	11.13	51.70	0.80	0.51	0.08	2.42	0.70
South Quartzite	0.05	6.35	32.90	62	0.90	309	9.01	38.50	0.76	0.46	0.10	2.53	0.59
Jeppestown Shale	0.53	19.00	50.30	103	2.38	389	17.49	56.50	0.91	2.16	0.54	3.55	0.75
Jeppestown Shale	0.56	18.48	48.80	-	1.70	362	20.39	64.70	1.55	2.32	0.56	4.62	1.32
Jeppestown Quartzite	0.11	12.40	25.30	71	1.45	335	21.03	48.10	1.18	1.92	0.32	3.61	0.63

TABLE 23

TRACE ELEMENT CONTENT OF KIMBERLEY STRATA IN THE DURBAN ROODEPOORT DEEP MINE, WEST RAND FLUVIAL FAN

Element	Conglomerates		Quartzites
Gold	1.00	ppm	0.03
Uranium	10	ppm	6
Thorium	7	ppm	5
Sodium	0.04	%	0.05
Potassium	0.08	%	0.10
Barium	60	ppm	50
Rubidium	10	ppm	7
Caesium	0.60	ppm	0.50
Lanthanum	15	ppm	15
Cerium	35	ppm	30
Neodymium	20	ppm	10
Europium	0.50	ppm	0.50
Terbium	0.20	ppm	0.20
Ytterbium	1.20	ppm	1.00
Lutetium	0.20	ppm	0.10
Titanium	0.15	%	0.08
Zirconium	160	ppm	130
Hafnium	3.50	ppm	3.50
Tantalum	0.50	ppm	0.50
Tungsten	0.50	%	0.60
Gallium	5	ppm	5
Iron	1.30	%	0.20
Scandium	4	ppm	3
Chromium	90	ppm	90
Cobalt	30	ppm	6
Nickel	45	ppm	25
Arsenic	30	ppm	30
Antimony	0.30	ppm	0.30

extent by the volume of pyrite and other sulphides that are present in the carbon. A striking feature is the very high gold content of the carbon - Carbon Leader and Main Reef Leader - in the bottom half of the Main-Bird Group, and the very low gold content of the carbon in the Bird Reef in the upper part of the same group.

TABLE 24

COMPOSITION OF CARBON SEAMS IN UPPER WITWATERSRAND STRATA

	A	B	C	D	E
Specific Gravity	1.35	1.51	<1.30	<1.63	<1.63
Moisture - %	0.88	3.70	3.84	1.28	4.00
Volatiles - %	18.41	22.65	16.82	12.34	18.76
Fixed Carbon - %	66.45	52.35	61.84	61.05	65.34
Ash - %	14.26	21.30	17.50	25.33	11.90
Sulphur - %	2.77	1.04	2.32	1.91	2.50
Gold - ppm	2397	9103	32	-	1073
Silver - ppm	220	768	10	-	80
Gold : Silver	10.89	11.86	3.29	-	13.39

A : Carbon Leader Reef, Doornfontein Mine, Carletonville Fluvial Fan

B : Carbon Leader Reef, West Driefontein Mine, Carletonville Fluvial Fan

C : Bird Monarch Reef, Luipaards Vlei Mine, West Rand Fluvial Fan

D : Kimberley May Reef, Vogelstruisbult Mine, East Rand Fluvial Fan

E : Main Reef Leader Reef, Vogelstruisbult Mine, East Rand Fluvial Fan

The gold which is recovered from the various reefs produces a bullion which is composed of 88-90 per cent gold and 7-11 per cent silver. Other metals which are present in the bullion are mainly copper, lead, zinc, and iron, together with traces of the platinum group of metals, notably osmiridium. The gold itself contains silver, copper, nickel, and mercury (Liebenberg, 1973).

Relationships Between Components

The gold content of the reefs is highly variable from point to point, both laterally and vertically within the mineralized horizon, and there have been many attempts to find other components of the reefs, which have a much lower variability but a high correlation with the general tenor of gold mineralization. Saager and Esselaar (1969) carried out an extensive investigation of the Basal Reef in the Welkom Goldfield, employing factor analysis, and obtained the results which are presented in Table 25. A high correlation was found to exist between gold and uranium and between gold and silver. In that the silver is alloyed with the gold, its variability within and between samples is as high as that for the gold. Liebenberg (1973) studied a larger number of reefs, and found the same relationship between gold and silver and between gold and uranium. The correlation he found between gold and some of the heavy and light minerals of the conglomerate horizons is listed in Table 26.

The silver which is intimately related to the gold is present to the extent of 8.9-12.3 per cent of the gold, with an average content of 10 per cent. The composition of the gold that is

TABLE 25

METAL CONTENT OF BASAL REEF IN THE FREE STATE GEDULD MINE,
WELKOM FLUVIAL FAN

Metal	ppm	high correlation
gold	375	Au + Ag
silver	36	Au + U
uranium	937	U + Ag
nickel	253	U + Pb
cobalt	156	Ni + Co
copper	212	
lead	448	
zinc	99	
sulphur	6.3%	

TABLE 26

CORRELATION (BY CHEMICAL ANALYSIS) OF MAJOR COMPONENTS
OF CONGLOMERATE REEFS

Components	Correlation
gold : silver	very close
gold : silver : uranium	close
gold : zirconium	significant
gold : chromium	significant
uranium : zirconium	significant
uranium : chromium	significant
gold : titanium : iron	inconclusive
gold : uranium : potassium	none

closely associated with the carbon seams shows a different pattern of silver content to that of the bulk of the gold present in the conglomerates. The spread is narrower, ranging between 7.7 and 11.0 per cent. There is a stratigraphic variation in the silver content of the gold, as indicated in Table 27, prepared from data supplied by Liebenberg (1973). It has also been shown that, more often than not, the silver content of gold in the proximal portions of the fans is higher than that of gold in the more distal facies. In hydrothermal deposits, there is generally an increase in silver content of the ores with depth. Thus, the increase in silver content of stratigraphically higher reefs in the Witwatersrand Basin might be due to the preferential recycling of the fanheads of previously deposited gold-bearing strata, or to the tapping of deeper gold with the progressive erosion of mineralization in the source-area.

The high correlation between gold and uranium is of a local nature within the reef. Over the whole of the fan, as mentioned previously, the greater concentrations of gold are upstream from the more pronounced uranium mineralization, so that the most payable gold-bearing areas do not coincide with the portions of the fan containing the maximum development of uranium ore. The higher

TABLE 27

STRATIGRAPHIC VARIATION IN SILVER CONTENT OF GOLD

Reef Horizon	Percentage Silver
Black	16
Ventersdorp	12
Elsburg	10
Bird	11
Main	5

amounts of gold are more likely to be in the conglomerate facies, while greater quantities of uranium are more probable in the pebbly quartzite facies (Minter, 1972).

The most conspicuous constituent of the reefs, after quartz, is pyrite, and many studies have been carried out in an attempt to correlate the amount of gold present and the volume of pyrite. Although Liebenberg (1973) has shown that there is a significant correlation between gold, uranium, chromium, and zirconium, all four elements are present in very small quantities, and neither of the last-mentioned two can be employed as a readily visible indicator of the degree of concentration of the first two. In certain sections of certain reefs, there is a definite correlation between the contents of gold and pyrite, as can be seen in Table 28, prepared for three reef horizons in the Village Main Reef Mine near Johannesburg. The correlation is strongest in the Banded Pyritic Quartzites. However, when the whole range of reefs is considered, there is no constant relationship between the pyrite and gold contents. Table 29 was compiled for a succession of mineralized horizons in the East Rand fluvial fan, and shows clearly that the ratio between pyrite and gold varies between very wide limits. The lack of constancy in the relationship mitigates against the visual employment of pyrite as a pointer to the amount of gold that might be present in any horizon, except under localized conditions.

TABLE 28

GOLD/PYRITE RELATIONSHIPS ON THE VILLAGE MAIN REEF MINE
IN THE EAST RAND FLUVIAL FAN

Gold Grade ppm	Weight Percentage of Pyrite		
	Banded Pyritic Quartzites	Main Reef Leader	South Reef
0- 10	7.0	0.5	1.4
10- 25	18.0	3.6	1.8
25- 70	21.6	3.3	3.0
70-170	30.5	4.5	3.6
>170	51.2	6.2	3.9

Cousins (1973) commented on the surprisingly uniform composition of the platinoids in the Witwatersrand reefs. Table 30 has been compiled from his data for the average composition of the platinoids in the various goldfields. The conspicuous feature about the relationships among the various metals is that iridium and osmium are much in excess of ruthenium, platinum, and rhodium, and that palladium is absent or in trace quantities only. It has been found that mature alluvial deposits contain osmium and iridium as the major platinoids, and that immature alluvials have predominantly platinum. Richer ores are generally the less mature ores. Cousins (1973) interpreted the ratios of platinoids in the Witwatersrand reefs as indicating that the waters of the basin were sufficiently chemically active to leach the platinum and the ruthenium, and that very mature platinoid deposits were formed.

TABLE 29

VARIATIONS IN GOLD/PYRITE RELATIONSHIPS STRATIGRAPHICALLY UPWARDS IN THE EAST RAND FLUVIAL FAN

Reef Group	% Pyrite : ppm Gold
Black	3.12
Kimberley	0.66
South	0.18
Main Reef Leader	0.36
Banded Pyritic Quartzites	1.80
Main	0.49

TABLE 30

AVERAGE PERCENTAGE COMPOSITION OF PLATINOIDS IN WITWATERSRAND REEFS

Goldfield	Iridium	Osmium	Ruthenium	Platinum	Rhodium	Palladium	ppb
Welkom	33.1	40.1	13.0	11.9	1.2	tr.	4.7
Klerksdorp	38.5	44.3	12.3	7.1	0.8	tr.	1.9
Carletonville	35.8	36.6	15.0	11.4	0.8	tr.	8.9
West Rand	36.0	39.9	13.7	9.8	0.8	tr.	2.4
East Rand	35.8	38.0	15.1	10.4	0.8	tr.	4.3
Evander	33.7	37.3	13.5	15.3	1.2	tr.	93.0
Average	35.3	39.2	13.7	10.9	0.9	tr.	11.8

The very low tenor of the platinoid mineralization is seen in the fact that the average content for all the goldfields is less than 12 parts per billion. The Klerksdorp field is impoverished in the platinoids, whereas the Evander field has a markedly higher concentration of the metals. The Kimberley reefs of the latter goldfield thus contain the maximum amounts of platinoids, but the Black Reef of the much younger Transvaal Sequence, where it occurs in the Witwatersrand Basin, is also rich in the platinum-group metals. The Black Reef is distinctive in having a higher pyrite content, a higher platinoid content, and a higher proportion of silver in the gold than most of the Witwatersrand reefs.

Grain-Size of Gold, Uranium, and Platinoids

The gold particles are present as thin platelets, sponge-like grains, crystalline octahedra, and irregular specks (Hallbauer, 1972). Most of the particles show signs of metamorphism and recrystallization. The flat, plate-like particles are the most widespread. Liebenberg (1973) reported that, where primary gold particles are seen, they are round, oval, or cylindrical in shape. The secondary grains are hackly, with serated outlines.

Hallbauer and Joughin (1973) undertook a grain-size frequency distribution study of gold particles in various reefs from various fluvial fans, the results of which are shown in Table 31. It is apparent that in many of the reefs mobilized gold has been redeposited on pyrite grains from which it is not readily detachable. All the gold that is larger than one millimetre in size was

TABLE 31

GRAIN-SIZE FREQUENCY DISTRIBUTION (PERCENTAGE) OF GOLD PARTICLES IN VARIOUS WITWATERSRAND AURIFEROUS HORIZONS

Reef	Fluvial Fan	<0.075 mm	0.075 - 0.15 mm	0.15 - 0.30 mm	0.30 - 1.00 mm	attached to coarse pyrite	attached to thucholite
Ventersdorp	West Rand	20	7	30	19	24	0
B	Welkom	30	17	10	7	3	33
Kimberley	Evander	51	11	23	7	8	0
Basal	Welkom	21	15	14	22	13	15
Vaal	Klerksdorp	25	22	18	15	5	15
Monarch	West Rand	31	4	20	40	0	5
South	West Rand	19	17	31	3	0	30
Carbon Leader	Carletonville	18	17	14	9	0	42

found to be attached to the large pyrite crystals. All gold less than 0.15 mm occurred as free gold. Particles in the carbon seams were seen to be nugget-shaped in many instances, their size being in the 0.05-2.00 mm range. Extremely fine-grained gold, less than 0.001 mm in diameter, occurs as thin fibres within the structure of the individual carbon columns.

The normal range in size of the gold particles is 0.005-0.5 mm (Hallbauer, 1972). The weight of these particles is between a few and 500 micrograms, but heavier grains of up to 60 000 micrograms have also been observed.

A comparison has been made between the sizes of the gold, uraninite, and platinoid particles from information provided by Coetzee (1966) and de Kock (1964), and this has been depicted in Table 32.

TABLE 32

GRAIN-SIZE FREQUENCY DISTRIBUTION OF GOLD, URANINITE, AND PLATINOID PARTICLES IN SOME WITWATERSRAND REEFS

Fluvial Fan	Reef	Mineral	Percentage frequency						
			.000-.015 mm	.015-.030 mm	.030-.060 mm	.060-.090 mm	.090-.120 mm	.120-.250 mm	>.250 mm
East Rand	Kimberley	Uraninite	3	37	46	11	2	1	0
Welkom	Basal	Uraninite	4	16	31	28	19	2	0
West Rand	Main	Gold	46	20	13	10	7	2	1
Carletonville	Carbon Leader	Gold	4	13	34	23	15	10	1
Carletonville	Carbon Leader	Platinoids	13	19	38	25	4	1	0

The average size of the gold grains is 0.035 mm, of the uraninite grains 0.065 mm, and of the platinoid grains 0.055 mm. All these figures illustrate the extremely small size of the minerals of economic importance in the reefs. No medium- to large-sized nuggets have been found during mining operations, and it can be concluded that, in regard to gold-particle size, the detrital deposits of the Witwatersrand are not comparable with modern-day placers.

THE CHARACTERISTICS OF A GOLDFIELD

Processes of Development

The weight of the evidence which has been gathered to date indicates that a goldfield is a fluvial fan, or fan delta, that developed where a major river, flowing from a source-area to the northwest, discharged into a shallow-water lake or inland sea. The depository took the form of a yoked basin, fault-bounded on the northwestern edge, which was shrinking progressively with time. Repeated tectonic adjustment took place along the active northwestern margin of the basin, with the source-area and earlier basin-edge deposits being uplifted relative to the downward-moving asymmetrical basin. Such uplift produced frequent steepening of the gradient of the paleoslope, which was accompanied by a regression of the apices of the fans from the shoreline towards the centre of the basin. The uplift of basin-edge material led to many cycles of reworking of previously deposited sediments, and this recycling was an important factor in the gradual concentration of gold and uranium until these components accumulated in economically exploitable amounts in the later stages of the life of the basin.

The fans are built up of cycle upon cycle of arenaceous and argillaceous material which was laid down on the interface between fluvial and lacustrine environments. Each cycle started with a high-energy pulse of sedimentation, consequent upon tectonic adjustment along the basin-edge, with succeeding pulses represented by lower and lower energy-levels, until conditions of non-deposition prevailed at the end of the cycle. The base of a cycle is thus marked by a regression, and the remainder of the cycle by transgressive conditions. The tectonic responses between cycles produced an unconformity, the sediments below which were laid down at the end of a transgression and the sediments above the unconformity at the beginning of a regression. Economic concentrations of gold, uranium, and other heavy minerals are optimally located along the more important of such unconformities, either on the plane of the unconformity itself or in the immediately overlying conglomerates.

The material was brought from the source-area on to the fan and distributed over its surface by a system of braided-stream channels. Interlacing of the channels often gives the impression of continuous sheets of gravel. Payshoots of higher gold and uranium values typically occur in the channels. However, greater amounts of heavy minerals also accumulated in interfluve areas, as the result of the winnowing of lighter components from the sands in which the gold was brought from the source-area to the fan. This winnowing was produced by either the braided streams themselves or by longshore currents active in the more proximal parts of the depository.

The longshore currents played a progressively more important role in the distribution of sediments on the fan and in the lake, as the transgression proceeded. Transgressive conditions probably reached their maximum in the penultimate stage of the cycle. In the time interval before the onset of the next regression, there was probably a period of stillstand, when incipient tectonic adjustment caused gentle tilting of the strata and when degrading conditions were prevalent, rather than the normally dominant aggrading processes. Estuarine or deltaic mud- or sand-flat conditions assumed major importance on the margins of the fan and along the lower midfan and fanbase sections. The environment was then at its optimum for the growth of algal mats. The degrading processes were also particularly favourable for the winnowing out of light material and the consequent formation of residual concentrations of heavy minerals including gold and uranium. It is envisaged that the overall processes that were in operation during this terminal stage of a sedimentary cycle - incipient tectonic tilting, degrading hydraulic regimes, fluvio-deltaic-estuarine environments, maximum winnowing of earlier sediments, and optimum algal development - were some of the essential factors responsible for the genesis of the Witwatersrand goldfields.

Final Responses to Processes

The best-developed fan that has so far been recorded in the Witwatersrand Basin is that of the East Rand. It is the largest known, and the one that has been mined most extensively. Figure 10 illustrates the main components of this typical gold- and uranium-bearing fluvial fan. The apex was located in a synclinal downwarp between two granite domes. The fan as a whole was also contained between domes of basement granite which were in existence before the fan was deposited, which continued to rise during sedimentation, thereby influencing the geometry of the fan and the lithofacies, and which were still active after the cessation of sedimentation, causing the faulting and folding which were responsible for the present morphology of the fan.

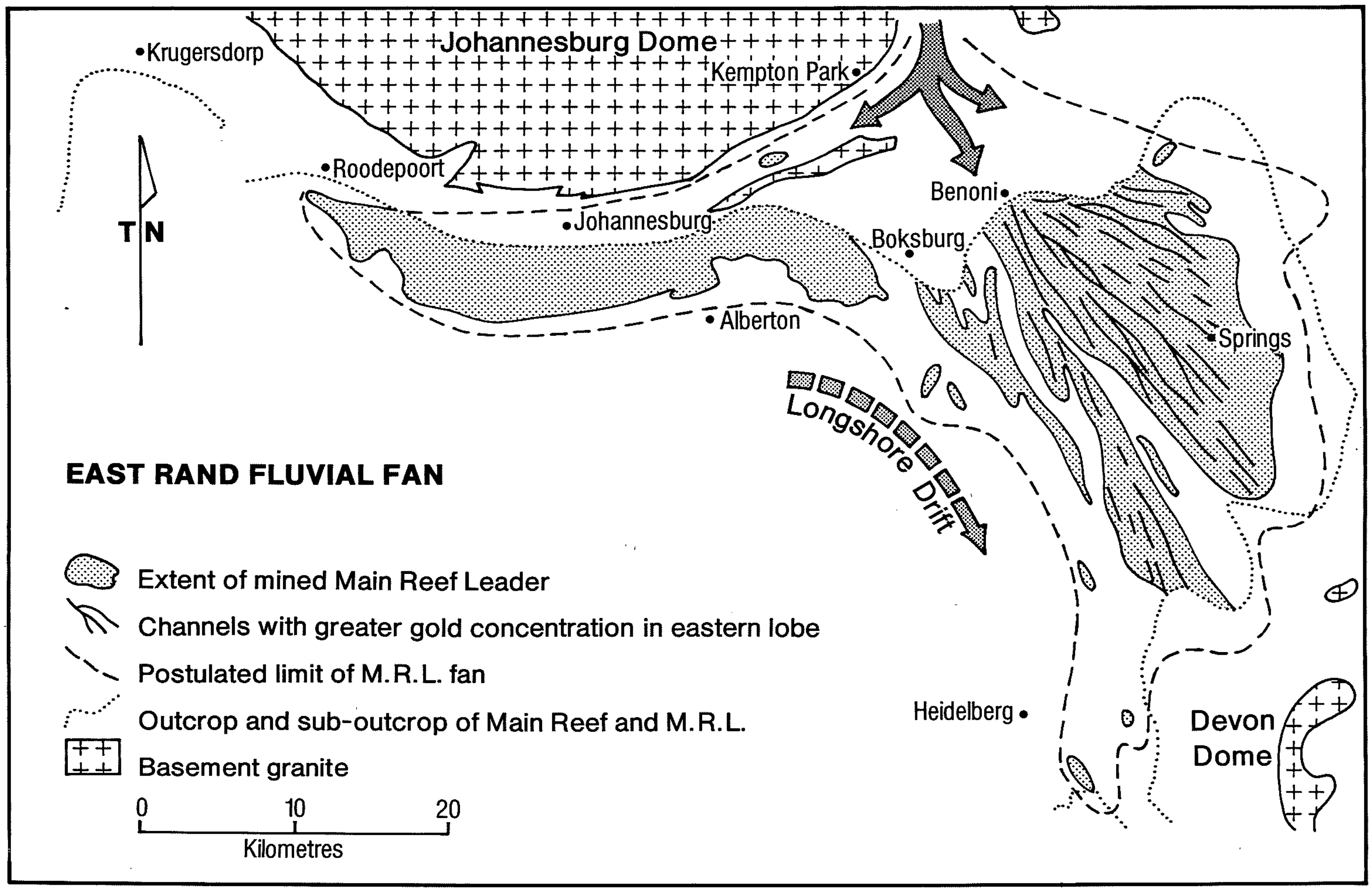
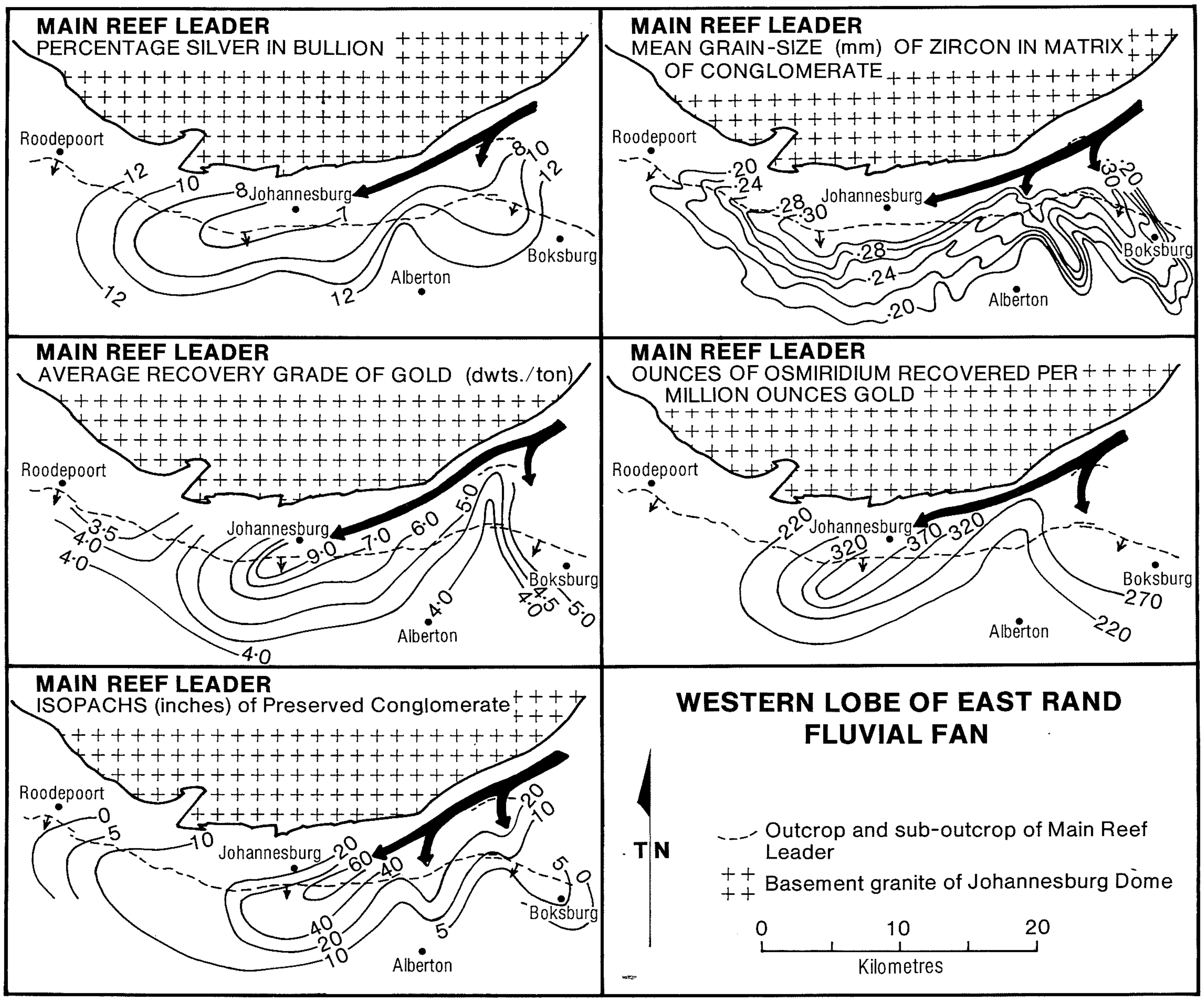


Figure 10 : The main components of a typical fluvial fan in which optimum mineralization is found. The western lobe forms part of the Central Rand Goldfield and the eastern lobe the whole of the East Rand Goldfield. The original fan covered at least 1 300 sq. km. The asymmetry of the fan is typical, with the left-hand lobe always larger than the right-hand, due to the influence of clockwise longshore currents.

Two main lobes were formed, with an intervening central portion of lower-energy sedimentation and attentuated stratigraphy. The fan was typically asymmetrical with the left-hand lobe (looking towards the basin centre) much larger than the right-hand lobe. Possibly, the main cause of the asymmetry was the direction of clockwise flow of the longshore currents, which tended to sweep the material brought on to the fan farther out in a southeasterly direction. On each lobe numerous channels formed (only those on the left-hand lobe are shown in Figure 10), which assumed a braided pattern radiating out from the apex of the fan. Clusters of channels generated second-order lobes on the major lobes, and three of these are present in the eastern section of the fan. The channels contain higher concentrations of heavy minerals, and constitute the payshoots which are preferentially mined.

The gross characteristics of the western, left-hand lobe are presented in Figure 11. The stratigraphic horizon on which the Main Reef Leader was formed has been studied in detail. The isopachs of the preserved thickness of the conglomerate reef are at their maximum down the centre of the lobe, with two smaller protuberances down the paleoslope off the main channel. The average recovery grade of gold reaches its highest values in the main channel; the ounces of osmiridium recovered per million ounces of gold also do so. The percentage silver in the bullion is lowest in the centre of the lobe, as would be expected in a typical alluvial deposit where more pronounced movement of water down the main channel would have tended to leach out greater amounts of silver.



<u>Figure 11</u> : *Some of the characteristics of the western lobe of the East Rand fluvial fan. Away from the centre of the main channel, the thickness of the preserved conglomerate decreases, the gold values drop off, the concentration of platinoids diminishes, the percentage of silver in the gold increases, and the grain-size of zircon in the matrix of the conglomerate becomes smaller. Similar patterns can be seen in subsidiary channels forming down the paleoslope from the main channel.*

Even down the subsidiary channels there is an impoverishment in silver. The contours of the mean grain-size of zircon in the matrix of the Main Reef Leader conglomerate clearly reflect the overall geometry of the western lobe, and show a close correlation with the thickness of the reef. Bigger zircon grains are present in the main channel and the two subsidiary channels. The gold values can also be correlated with the zircon grain-sizes, the limit of payability being demarcated by the 0.20 mm contour line.

The properties of the reef described above point strongly to the intimate relationship between sedimentary processes and the mineralization of the conglomerate horizon. The gold and uranium were concentrated to varying degrees in different localities, in response to variations in the hydraulic regime that prevailed at a particular period of time during the infilling of the

Witwatersrand Basin. The processes of ore-formation came into operation on less than twenty occasions during the laying down of more than 8 000 metres of sediments, the deposition of which could have occupied 100-250 million years. The generation of auriferous and uraniferous syngenetic sedimentary ore-bodies was a rare phenomenon.

A detailed study of the facies variations down the lobe of a fluvial fan has been carried out by Sims (1969) for the Basal Reef in the Welkom Goldfield. These changes have been summarized in Table 33, in which it can be seen that all the gradations in properties are in accord with those that would be produced in a fluvial system in which the competency of the streams diminished down the paleoslope, and the energy-level of the hydraulic regime decreased from the proximal to the distal portion of the fan that was being built into the depository by the streams.

TABLE 33

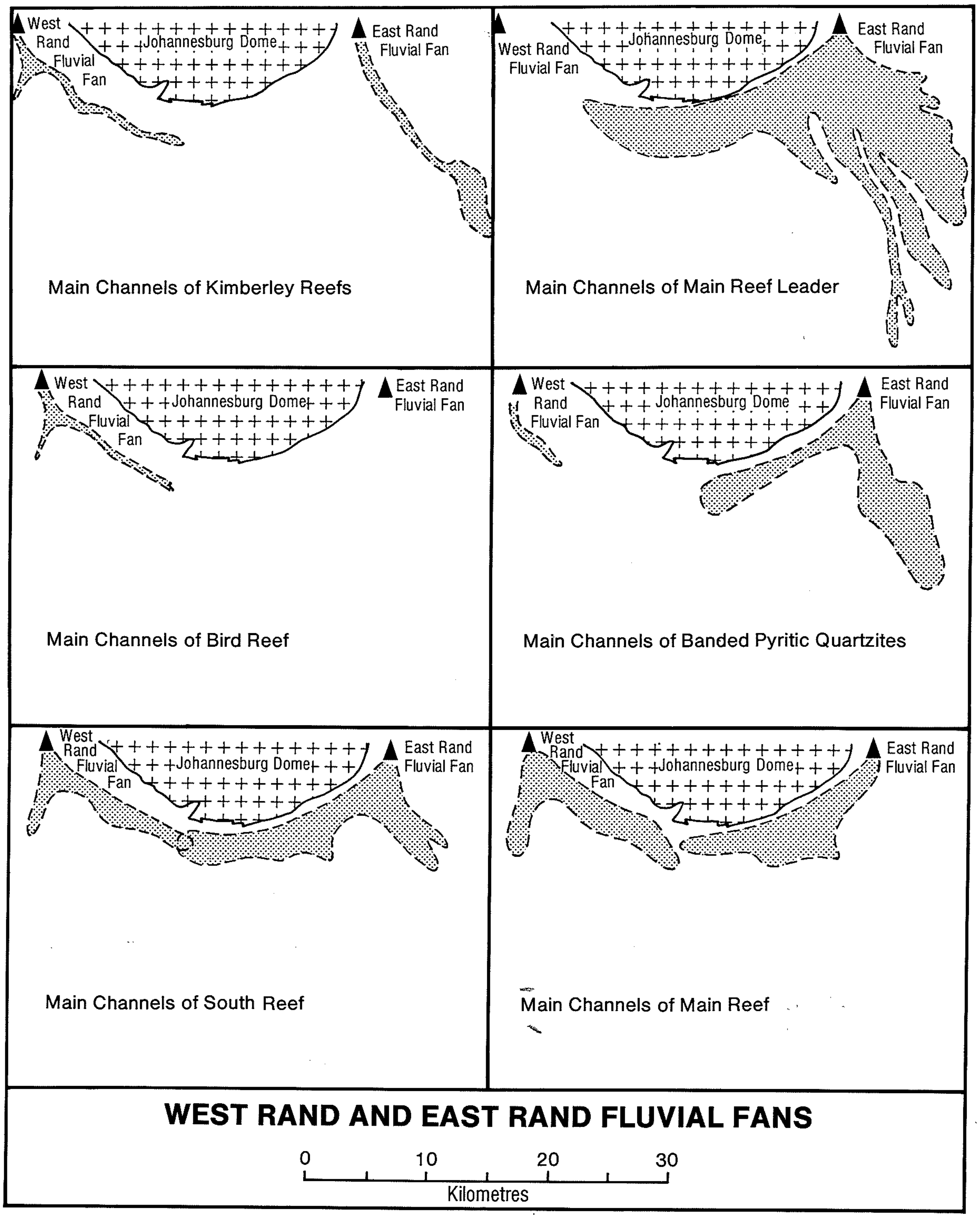
VARIATIONS BETWEEN PROXIMAL AND DISTAL FACIES OF BASAL REEF IN THE SOUTHERN PART OF THE WELKOM FLUVIAL FAN

	Massive Southern Reef	Multiple, Late-Channel Reef	Central, Double Reef	Northern, Single Reef
zone thickness (m)	1.5	4.5	1.8	0.9
conglomerate % of zone	65	45	25	25
nature of conglomerate	massive	6 bands	2 bands	1 band
pebble size	largest	smaller	still smaller	smallest
composition of conglomerate	polymictic	polymictic	oligomictic	oligomictic
lower boundary surface	very irregular	devoid of pebbles	largest pebbles	carbon seams
cleanness of quartzites	very dirty	dirty	clean	very clean
grain-size of quartzites	coarse	coarse	medium	fine
cross-bedding	obscure	well-developed	well-developed	abundant
pyrite content	abundant, large	abundant, medium	minor, small	minimal, small
carbon specks	very rare	occasional	plentiful	plentiful
carbon seams	absent	absent	present	frequent
distribution of gold	throughout	internal bands	bottom contact	bottom contact
uranium values	very low	very low	higher	highest

Sequential Development of Adjacent Fans

Where fans were relatively close to each other, the processes of sedimentation interacted, and the margin of one fan merged, almost imperceptibly, into the margin of the other. The best example of this is seen in the West Rand and East Rand fans. The western lobe of the East Rand fan overlapped the eastern lobe of the West Rand fan, in the vicinity of Johannesburg, to give the appearance of a single environment of continuous deposition. The area of intermingling of the two lobes is known as the Central Rand Goldfield, which now can be regarded as a geographic term only, and not the expression of a discrete fluvial fan.

Figure 12 has been prepared to show the relative degrees of activity at any one particular period of time on the two adjacent fans. The sizes of the main channels of Main Reef deposition are about the same for the West Rand and East Rand fans. Both lobes were forming in the West Rand, but only the western lobe of the East Rand was active. When the Banded Pyritic Quartzites were being formed, the East Rand was subjected to more intense sedimentation, with both lobes being constructed. Only one lobe of the West Rand fan, however, was receiving material. During Main Reef Leader times, all activity was focused on the East Rand fan, with both lobes building out to a very marked extent.



<u>*Figure 12*</u> : *The relative amounts of coarser sediments deposited at particular times on the adjacent West Rand and East Rand fluvial fans. The main channels are portrayed that were formed during Main Reef, Banded Pyritic Quartzites, Main Reef Leader, South Reef, Bird Reef, and Kimberley Reef times.*

The West Rand fluvial system does not seem to have been in operation. When the South Reef was being deposited, the East Rand fan was much less active than in Main Reef Leader times, and the West Rand depositional processes were once again operative. The East Rand fan appears to have received no auriferous sediments during Bird Reef times, and the West Rand fan only a relatively small volume.

In Kimberley times, the East Rand fan was reactivated, and sedimentation on it was of greater importance than on the West Rand fan.

The variations in relative activity of the two fans are diagrammatically depicted in Figure 13. The East Rand fan received a greater amount of sediment overall, a fact which is reflected in the greater amounts of gold which have been won from mines in this fan. The period of active sedimentation in each fan seem to have had a see-sawing relationship, as can be seen in the peaks and depressions in the curves drawn through the bars of the diagram. Whenever abundant sediment, carrying gold and uranium, was brought down to one fan, the transportation and depositional system on the other fan was markedly diminished in importance. The cause of this phenomenon probably lay in relative differences in response to non-uniform tectonic disturbances in the uplifted source-area. Wherever fault-blocks of source-material were lifted higher, the drainage-system off those blocks received greater amounts of erosional debris, and the fan into which the particular system ultimately discharged was consequently subjected to more intense sedimentation than the adjacent fan that was served by a source-area in which uplift had been relatively slight.

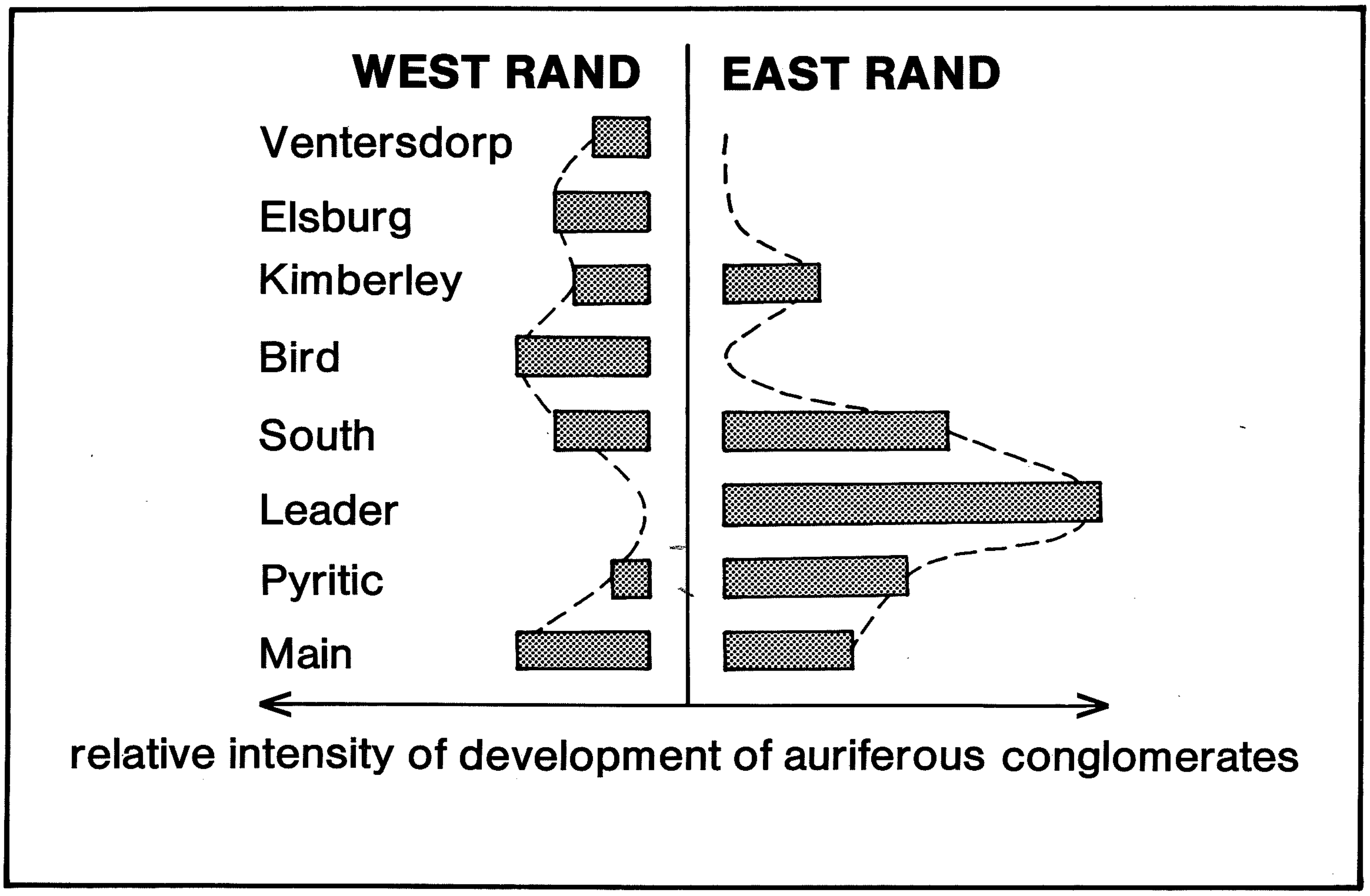


Figure 13 : *A diagrammatic representation of the waxing and waning in the intensity of auriferous conglomerate development on the West Rand and East Rand fluvial fans. The diagram has been prepared from the information in Figure 11. There is an antipathetic relationship apparent, so that appreciable development of conglomerate on one fan is contemporaneous with minimal deposition on the adjacent fan.*

Progressive Development of a Goldfield

A goldfield is a basin-edge feature. Over the whole history of the basin, its dimensions diminished, so that the basin-edge, in a broad context, was a regressing feature. This would imply that each stratigraphically higher fan would have been located farther out towards the depositional axis of the basin. Because the basin-edge was an active fault-environment, the more proximal portions of earlier fans would have been subjected to uplift, erosion, and recycling into later fans. Cannibalization was an integral process in the formation of auriferous fans.

The full sequence of events in the history of development of a goldfield is best seen in the Klerksdorp field, and has been illustrated in Figure 14. The same fluvial system moving down the paleoslope from the northwest, and confined between uplifted granite domes, formed a series of fans, starting with the Dominion Reef and ending with the Kimberley Reefs. The positions of the apices of the fans changed from time to time, but generally remained within a relatively narrow zone. The apex of the oldest fan is fartherest to the northwest, and the apex of the youngest fan closest to the centre of the basin. The larger fans show the asymmetrical geometry produced by the interaction of the transporting fluvial system and the distributing lacustrine system.

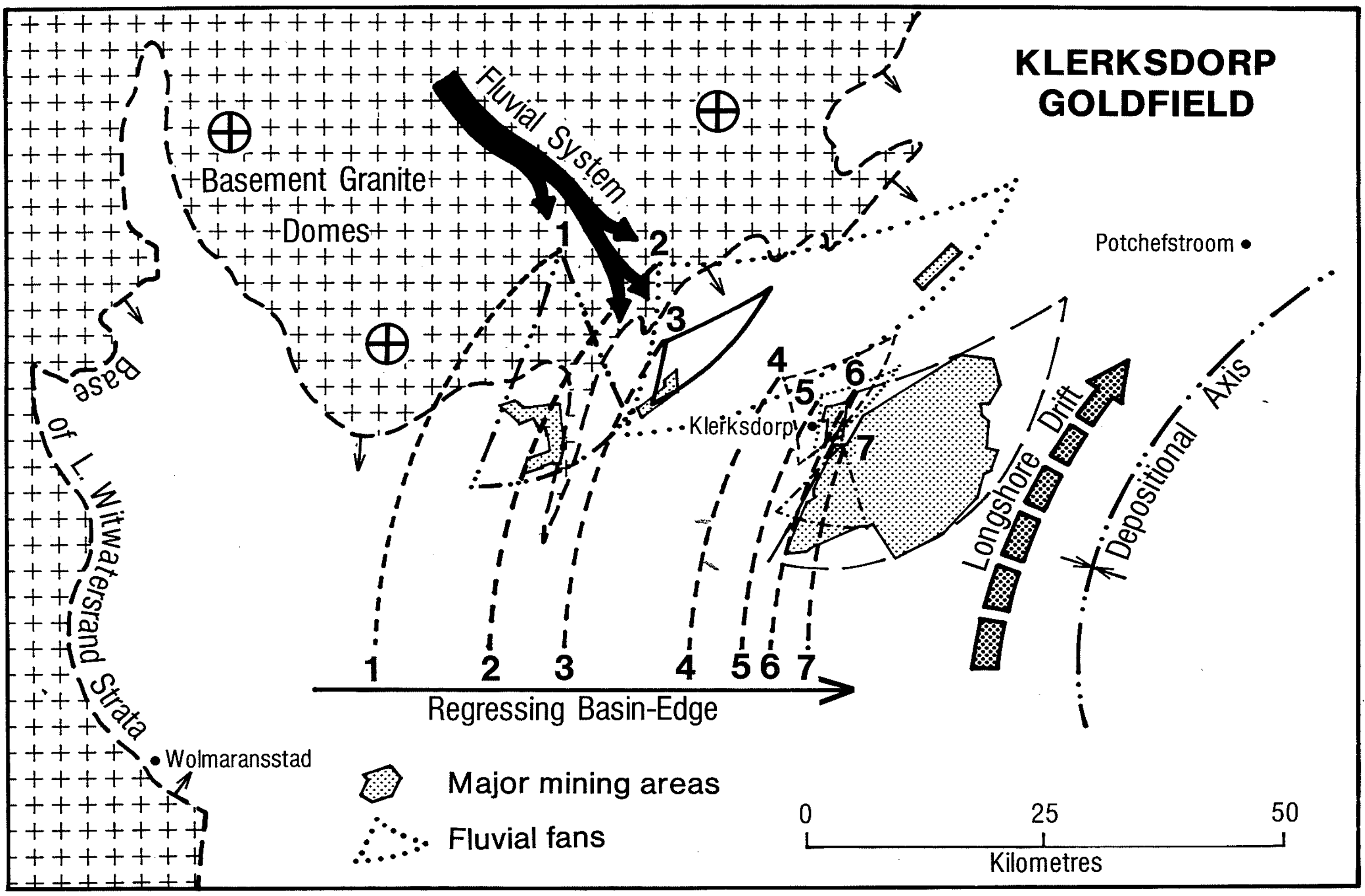


Figure 14 : The regressive nature of the basin-edge in the Klerksdorp Goldfield. The apices of successive fans move from the basin-edge towards the depositional axis. 1 = Dominion Reef; 2 = Government Reefs; 3 = Jeppestown Reefs; 4 = Main Reef; 5 = Livingstone Reef; 6 = Bird Reef; 7 = Kimberley Reefs. The consistent position of the fluvial system between granite domes over a long period of time is apparent. Increasing structural instability is indicated by the more frequent development of fans in the Upper Witwatersrand Division (4, 5, 6, 7). Left-handed asymmetry of the fans, due to clockwise longshore drift, is also discernible.

Increasing structural instability with time is apparent in the greater number of fans developed during Upper Witwatersrand sedimentation than during the formation of the Lower Witwatersrand Division. The apices of the Upper Witwatersrand fans were also closer to each other than were those of the Lower Witwatersrand period. The formation of a fan was the response to tectonic adjustment across the fault boundaries of the yoked basin, and the more frequently major movement took place, the more frequently were fans formed.

THE SOURCE OF THE GOLD AND URANIUM

The six goldfields which have thus far been found in the Witwatersrand Basin are all located along the northwestern edge of the depository. The paleocurrent directions support the gross sedimentological indications that the source-area of the detrital material, including heavy minerals, was to the northwest of the region now occupied by the portion of the basin which has been preserved from erosion. Material was introduced from the southwestern edge of the basin, but the volumes were smaller, the energy-levels lower, argillaceous components more abundant than arenaceous, and only uneconomic amounts of gold and uranium introduced, for the most part. The evidence thus points to the fact that the source of the gold and uranium lay to the northwest of the basin.

It is believed that the pre-Witwatersrand rocks which, on erosion, gave rise to the sediments that filled the basin were members of a typical Archean assemblage of a granite-greenstone terrane. Most of the postulated source-area is presently covered by younger Proterozoic sequences of impressive dimensions, such as the Ventersdorp lavas, the Transvaal sediments, and the Bushveld Complex. Consequently, there are only a few windows onto the pre-Witwatersrand rocks, but all of these show only Archean strata and no other pre-Witwatersrand sequences. The rock-types that have been observed are similar to those found in the classic area of the Barberton Mountain Land, where a full succession of very early granite-greenstone rocks has been preserved. The topmost members of the succession are the Moodies sediments which were deposited in a continental environment; the middle members are the Fig Tree greywacke-turbidite sediments, formed under marine conditions; and the lowermost members are the ultramafic, mafic, and acid members of the Onverwacht group of igneous rocks which were extruded in a marine environment. The Onverwacht Group consists of a lower division, where ultramafic rocks are abundant, mafic rocks very well-developed, and acid rocks present to a very limited extent. In the upper division, the ratio of mafic to ultramafic rocks increases substantially, and there is a greater volume of acid material than in the lower division. Most of the gold mineralization is located along two stratigraphic horizons, the unconformities between the Lower Onverwacht and the Upper Onverwacht and between the Upper Onverwacht and the Fig Tree. No uranium mineralization has yet been found in any of the greenstone belts of the Kaapvaal Craton.

According to Liebenberg (1973), 30-86 per cent of the gold in the Barberton Mountain Land occurs in a free form, while 14-70 per cent is intimately associated with sulphides, mainly pyrite and arsenopyrite. The average size of the grains of gold is 0.005-0.05 mm, with the free particles generally larger than those in the sulphides. Pink gold is occasionally present in the Barberton mines, the pinkness resulting from the gold being alloyed with nickel. The only other place where such gold has been found in South Africa is in the Dominion Reef, at the base of the Witwatersrand succession.

The gold content of the ultramafic and metabasaltic rocks of the Barberton Mountain Land varies between 0.005 and 0.01 ppm. Where the rocks have been weathered and recycled, the gold content rises to 0.075 ppm. The tenor of gold in the associated granites is less than 0.005 ppm. The average recovery grade of the Witwatersrand reefs is two orders of magnitude greater than the gold content of the reconstituted lavas of the Onverwacht Group.

The nature of the heavy minerals in the Witwatersrand reefs is a pointer to the composition of the source-rocks from which the mineralization was drawn. The diagnostic minerals can be placed in at least two groups. The platinoids, chromite, diamonds, and cobalt and nickel sulphides were probably in ultramafic rocks originally. The uraninite, zircon, cassiterite, garnet, and quartz were probably drawn from granitic members of the pre-Witwatersrand basement. It is possible that some, at least, of the pyrite and copper sulphides were originally in the acid volcanics of the Upper Onverwacht Division.

The age of detrital uraninite in the basal members of the Witwatersrand Sequence has been determined at 3 040 ± 100 m.y., and of detrital monazite at 3 160 ± 100 m.y. Both of these ages are younger than the topmost rocks of the Archean greenstone sequence in the Barberton Mountain Land, which are older than 3 250 m.y. The age of the granitic basement which underlies the Witwatersrand rocks is 3 050 - 3 200 m.y., younger than the Moodies rocks, and the uranium-thorium mineralization is probably a product of the processes involved in the emplacement of the granitic basement.

Köppel and Saager (1973) reported that the isotopic composition of the lead in some of the detrital sulphides in the Witwatersrand reefs is similar to that of lead in galena from certain mines in the Barberton Mountain Land.

The conclusion is that the minerals of economic importance in the Witwatersrand Basin were drawn from two different populations of mineralized rocks in the Archean granite-greenstone terrane which lay to the northwest of the depository. The gold came from the ultramafics and mafics of the greenstone belts, while the uranium came from the younger granites which enveloped the belts. Depending upon the relative volumes of the two different source-rocks, that were being eroded at any particular time, and upon the overall status of the hydraulic regime which denuded, transported, and deposited the weathered material, varying quantities of gold and uranium, relative to each other, were concentrated in the sediments at different stratigraphic horizons.

The transition from Archean-type crustal evolution to Proterozoic-type took place in South Africa between 3 000 and 3 250 m.y. ago, 500 m.y. earlier than on the Canadian Shield where the first continental sedimentation commenced at about 2 500 m.y. In addition to this time difference, there are also major dissimilarities between the gross compositions of the greenstone belts of Canada and South Africa. Those of Canada contain substantially greater volumes of acid volcanics, while those of South Africa are dominated by ultramafics. The Canadian belts are hosts to gold, copper, and zinc mineralization; the South African belts are devoid of copper and zinc, and the most important sulphide ores are those of antimony. The South African greenstones are hosts to essentially siderophile mineralization, while those of Canada have both siderophile and chalcophile ore deposits. Since it is believed that the source of the Witwatersrand gold was in the ultramafics and mafics of the greenstone belts, the much greater volumes of such rock-types in South Africa, compared to the Canadian Shield, might offer an explanation, in addition to that of the greater age of Proterozoic sedimentation, for the uniqueness of the Witwatersrand gold mineralization.

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