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THE SOURCES OF WITWATERSRAND GOLD AND URANIUM : 'A CONTINUED DIFFERENCE OF OPINION'

D. A. PRETORIUS

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UNIVERSITY OF THE WITWATERSRAND
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by

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ABSTRACT

The Witwatersrand Basin hosts the most-productive goldfields yet mined anywhere in the world. From 1886 to the end of 1987, a total of 41,700 metric tons (1.340 billion ounces) of gold and 146,000 metric tons of uranium oxide has been recovered from mineralized quartz-pebble conglomerates, quartzites, and thin layers of kerogen deposited, between 2750 and 3100 Ma ago, on braid-deltas and braid-plains marginal to a northeasterly-trending, shallow-water lake.

There is general agreement on the magnitude and extent of the concentrations of gold and uranium and on the depositional environment of the sediments, but, certainly, not on the nature and origins of the mineralization. Disagreements revolve about the source, genesis, and mode of emplacement of essentially four components of the ores : gold, uraninite, pyrite, and kerogen. Another 70 ore-minerals also contribute to the controversy, but rarely advance to the centre of the stage. Syngeneticists subscribe to a paleoplacer interpretation of the stratabound mineralization, their preference being founded primarily on sedimentological evidence. Epigeneticists, arguing from mineralogical and geochemical bases, tend to favour the preferential migration of hydrothermal fluids through the more-permeable horizons of coarser clastics. A partial reconciliation has been effected through the modified-placer theory, which envisages the reconstitution of originally-detrital heavy minerals by post-depositional, hydrothermal activity, associated with, possibly, up to four episodes of post-depositional metamorphism. No theory has been proposed yet, which offers promise of a resolution of the many differences of opinion.

Past approaches to deciphering the history of mineralization in the Witwatersrand Basin have concentrated on the host-rocks within the depository. Presently, attention is being focused on prospective provenance-regions outside the known limits of the depository and on the place of the basin and its successors in the tectonic evolution of the Kaapvaal Craton. The long-held concept of Archean greenstone-granite terrane's being the source of detrital gold and uraninite has receded, mainly because of differences in compositions of the ore-minerals and because, volumetrically, even the most productive of the world's greenstone belts falls far short of qualifying as an adequate source of the gold in the Witwatersrand strata, if it be paleoplacer. The most-recent basin-analysis suggests that, instead of representing a yoked, intracratonic, Early-Proterozoic depository, the Witwatersrand Basin might have developed in a foreland, back-arc environment of Late-Archean age.

Consideration is being given now to the hydrothermal fluids' having been formed by metamorphic dehydration of thick argillite successions in the lower part of the stratigraphy. Another line of thought is that pyritic, auriferous exhalites formed by shallow-marine, hydrothermal discharge in the early stages of the basin's development and that the endogenous, primary mineralization was eroded subsequently, to supply detrital gold to the stratigraphically-higher part of the basin-fill. Extensive, hydrothermally-altered granitic rocks have been found to have been emplaced, during the waning stages of the depository's history, in a postulated source-area close to the basin's presently-known limits, and research is being furthered into the possibility that the intensely-mineralized roof-zones and cupolas of these HAGS were exogenous sources of gold and uranium. One more, novel source-area, the

idea of which is being explored presently, is the magmatic arc which ought to have evolved, if the Witwatersrand Basin is, indeed, a product of a foreland, back-arc environment. Along the repeatedly-reactivated interface between magmatic arc and back-arc basin, pene-contemporaneous granite emplacement, hydrothermal alteration and mineralization, tectonic uplift, deflation and erosion, chemical-charging of surface-waters, fluvial transportation, sedimentation on braid-deltas, introduction of ore-minerals, and physical re-working of clastics within the depository possibly followed each other in rapid succession, over and over again between 2750 and 2850 Ma ago, when the terminal chapters of basin-formation were being recorded. This scenario depicts the Witwatersrand reefs as the consequences of coeval convocations of hydrothermal, precipitation, and placer processes prevailing in the Golden Age of the Late-Archean.

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The Mineralization of the Witwatersrand Basin

".... perhaps no metallic deposit has exercised the minds of economic geologists as regards origin as much as the gold-bearing quartz-pebble conglomerates since their discovery in the Witwatersrand of South Africa in 1886."

- R.W. Boyle (1987)

The Status of the Rand Goldfields

No matter how great the differences of opinion on the genesis of the gold and uranium mineralization, nor how wide the range of arguments on the original depositional environments of the host-sediments, it can be stated, without fear of contradiction or suspicion of exaggeration, that the Witwatersrand goldfields remain as the greatest producers of the precious metal the world has ever known. Although annual output has declined from a peak of 1000 tonnes of gold, in 1970, representing 67 percent of total, world mine-production, to 578 tonnes, in 1987, the Witwatersrand still accounted for 34 percent of all gold won from all countries in the latter year. Perhaps, a more-impressive picture of this ore-deposit can be painted by covering the whole canvas, stretched over 101 years, from the discovery of the gold-bearing conglomerates, in March, 1886, near Johannesburg, and the production of the first gold, in May, 1887, to the end of 1987 (Table 1).

TABLE 1

TOTAL GOLD- AND URANIUM-PRODUCTION FROM THE WITWATERSRAND BASIN

	Gold	Uranium Oxide
Period	1887-1987	1952-1987
No. of Mines	153	31
Total Recovery (tonnes)	41 715	145 389
Total Ore Milled (million tonnes)	4 472	675
Mill-head Grade (grammes/tonne)	9,32	215

To attempt an even-more broad-brush measure of the status of the Witwatersrand, its contribution to the gold won by all of mankind during the past 6000 years might be estimated, bearing in mind how very approximate such a figure, of necessity, must be (Table 2). Since the Witwatersrand was discovered, it has yielded half of the world's total output; since the beginning of recorded time, about one-third.

The economics of mining for the years 1986 and 1987 are shown in Table 3, for gold, and in Table 4, for uranium. Tonnages and grades are indicated in metric units, but average unit-revenues and -profits have been determined per ounce, for gold, and per pound, for uranium, in keeping with conventional pricing

TABLE 2

THE WITWATERSRAND BASIN'S SHARE OF ESTIMATED WORLD GOLD-PRODUCTION

	World Production (tonnes)	WWR Production (tonnes)	WWR %
BC AD 4000-1886	31 400	-	-
AD AD 1887-1987	80 600	41 715	52
BC AD 4000-1987	112 000	41 715	37

practice for these commodities. With a total revenue, in 1987, of over $8 billion from gold and a combined total profit of $3,5 billion on the sale of gold and uranium, it is not unreasonable to claim that what the eminent American mining engineer, John Hays Hammond (1935), before the turn of the last century, called "..... the greatest of the world's goldfields - the Witwatersrand, the White Water Ridge", after more than a century since discovery, still ranks unsurpassed and unchallenged.

TABLE 3

GOLD-PRODUCTION AND -REVENUE FROM THE WITWATERSRAND BASIN

	1986	1987
total gold recovered (tonnes)	615,307	578,108
ore treated (million tonnes)	107,674	107,634
mill-head grade (grammes/tonne)	5,63	5,28
revenue from gold (billion US dollars)	7.204	8.164
average gold-revenue (US dollars/ounce)	364.17	439.27
average working-costs (US dollars/ounce)	187.82	264.16
total profit on gold (billion US dollars)	3.489	3.255
average profit on gold (US dollars/ounce)	176.35	175.11

Location of the Witwatersrand Basin

The Rand Basin is located in the Transvaal and Orange Free State provinces of the Republic of South Africa and is confined to the northeastern quadrant of the country. The central and northeastern segment of South Africa, in which can be included Lesotho and Swaziland, and the southern portion of Botswana are underlain by the Kaapvaal Craton. This crustal fragment and the Rhodesia Craton, to the north, constitute the two nuclei of the Southern African Shield which is circumscribed completely by younger terranes. The Kaapvaal Craton has dimensions of 1100 km on its northeastwards-trending long axis and 700 km along its short axis. On at least three of its four sides, its boundaries are formed by thrust-faults centripetally overriding the Kaapvaal Craton (Pretorius, 1985, 1986b).

TABLE 4

URANIUM-PRODUCTION AND -REVENUE
FROM THE WITWATERSRAND BASIN

	1986	1987
total U_3O_8 recovered (tonnes)	4 799,301	3 920,002
ore treated (million tonnes)	24,836	21,805
mill-head grade (grammes/tonne)	172	159
total profit on U_3O_8 (million rands)	468,180	505,935
(million US dollars)	204.875	248.465
average profit on U_3O_8 (rands/kilogramme)	97,55	129,06
(US dollars/pound)	19.36	28.75

The Witwatersrand depository is preserved in the southeastern half of the craton, and outlying, possible correlatives virtually abut against the southeastern-boundary thrust-zone. The northwestern half of the craton hosts younger Precambrian formations, lying on the same type of Archean 'basement' as do the Witwatersrand rocks. By far the greater part of the Rand Basin is covered by younger Precambrian and Paleozoic sequences, and its actual extent and shape have been delineated only as a consequence of more than 100 years of intensive subsurface exploration by core-drilling and geophysical surveying.

Basin Geometry and Sedimentary Fill

In 1986, the celebration of the centenary of the discovery of the Witwatersrand goldfields occasioned the presentation of a great volume of new data, the extent and detail of which compelled a comprehensive re-assessment of all aspects of the depository and its contained mineralization. Up to that time, the extent and shape of the basin were accepted, generally, to comply with that depicted in Figure 1. In addition to the seven major goldfields of Welkom, Klerksdorp, Carletonville, West Rand, Central Rand, East Rand, and Evander, two quite minor 'goldfields' - Venterskroon and South Rand - have been plotted, as well as 13 structural domes produced by intersecting fold-trends. The location and continued elevation of these culminations are considered to have played major roles in the siting and development of the various fields.

Triggered by the appearance of Borchers's (1960, 1964) benchmark maps of the whole of the depository and its surrounds, a series of basin-analyses was undertaken in order to establish the definitive parameters of the depository (Brock and Pretorius, 1964a and b; Pretorius, 1966, 1975, 1976a and b, 1984b, and 1985). From a synthesis and reconciliation of these studies, Table 5 was prepared as a first model of the characteristics of the Witwatersrand Basin, as suggested by surface mapping, extensive underground mining to a depth of 4000 metres, and the drilling of about 2500 cored boreholes. In a post-Centenary, second model (presented later), modifications have had to be made to all the parameters.

Far too-great a number of publications on the stratigraphy and sedimentology of the Witwatersrand Sequence have been consulted for the preparation of Table 6 to permit individual citing. The two substantial volumes on the Rand which were put out in 1964 and 1986 by the Geological Society of

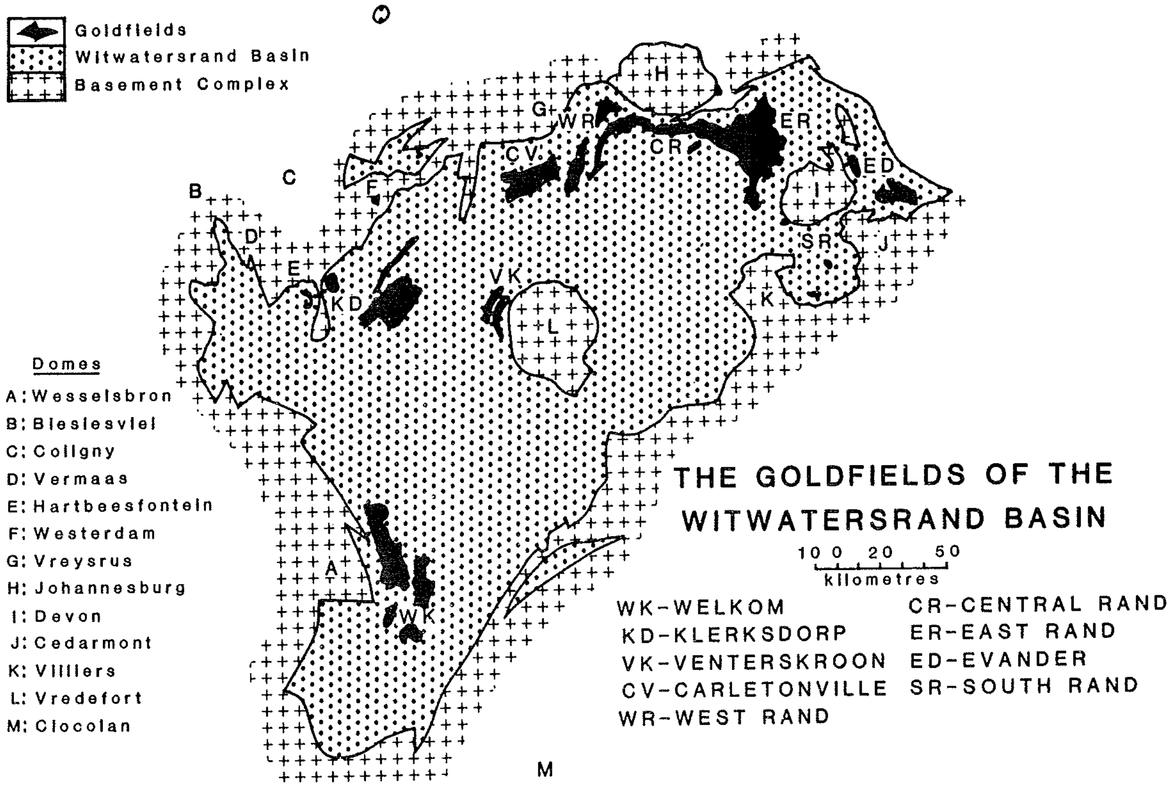

Figure 1 : *Regional geological map of the Witwatersrand Basin, showing its presently-known limits, the locations of the goldfields, and the positions of structural domes which have influenced the siting and development of individual fields.*

TABLE 5

BASIN ANALYSIS OF THE WITWATERSRAND DEPOSITORY : 1964-1986
FIRST MODEL OF DEFINITIVE PARAMETERS

Orientation of Basin	:	NE - 370 km; NW - 190 km
Shape of Basin	:	oval; asymmetrical; steep side on NW
Type of Basin	:	intracratonic
Development of Basin	:	lower division of sequence - progressively shrinking
	:	upper division of sequence - progressively shrinking
Age of Basin	:	2500-2800 Ma (anomalously-old E. Proterozoic)
Provenance	:	Archean (> 3000 Ma) granite-greenstone basement
Nature of Goldfield	:	a fluvial fan peripheral to a shallow lake

South Africa, under the editorships of S.H. Haughton and C.R. Anhaeusser and S. Maske, respectively, contain expansive information on these two aspects of Witwatersrand geology. It is to be appreciated that idealized figures have been presented in this table. The completeness of the stratigraphic succession, the thicknesses of the different groups, the sand:shale ratios, and the dominant lithologies, as to be expected, vary from field to field. In the northeastern, southeastern, and southwestern segments of the depository, the Dominion Group is missing.

TABLE 6

THE NATURE OF THE SEDIMENTARY FILL OF THE WITWATERSRAND BASIN

Central Rand Group	:	extends over an area of 26 000 sq. km.
	:	dimensions of known extent = 290 x 170 km.
	:	average thickness = 3 200 m.
	:	lithologies = dominantly coarse clastics; sand/shale = 13
	:	depositional environment = fluvial; minor lacustrine
West Rand Group	:	extends over an area of 43 000 sq. km.
	:	dimensions of known extent = 350 x 250 km.
	:	average thickness = 5 100 m.
	:	lithologies = coarse and fine clastics; sand/shale = 1
	:	depositional environment = marine shelf and tidal flat
Dominion Group	:	extends over an area of 13 000 sq. km.
	:	dimensions of known extent = 130 x 110 km.
	:	average thickness = 2 700 m.
	:	lithologies = volcanics; minor clastics; sand/shale = 6
	:	depositional environment = fluvial
Witwatersrand Sequence	:	known extent = 45 000 sq. km.
	:	dimensions of known extent = 390 x 250 km.
	:	average thickness = 11 000 m.

Stratigraphic Relations and Age

Either the Dominion or the West Rand Group rests on an Archean 'basement' constituted by granitic material, in the main, and by remnants of typical greenstone belts, to a much lesser extent. The age of this 'basement' is greater than 3200 Ma, and the contact with the Witwatersrand sediments is either sedimentary or tectonic. On the northwestern side of the depository, keels of the lowermost sections only of greenstone stratigraphies are preserved, suggesting that structural uplift and consequent erosion were of a higher order than on the southeastern rim. Up until the 1970's, it was thought that all the exposed granites around the basin belonged to the 'basement' and that, therefore, Witwatersrand sedimentation post-dated all granite magmatism, another tenet of crustal evolution that was to be guillotined during the wave of new thinking that started washing over the Witwatersrand at the beginning of the 1980's.

The Ventersdorp Sequence overlies the Witwatersrand rocks both conformably, in places, and unconformably, in other areas. It represents an impressive succession of andesitic-basaltic volcanics, containing, near its middle, a fair thickness of volcanoclastic and coarse-clastic sediments. Varying degrees of tectonism have removed greater or lesser proportions of the full Ventersdorp succession, and, in some parts of the Rand Basin, the sequence was either not emplaced or was removed entirely by erosion. The depositional axis of the Ventersdorp Basin shows a northwestwards displacement, relative to the Witwatersrand depo-axis (Pretorius, 1965, 1984b).

The Ventersdorp assemblage is succeeded by the Transvaal Sequence, the largest of the Precambrian basins on the Kaapvaal Craton. Chemical sedimentation is far-more pronounced than in preceding or succeeding sequences, and dolomites and iron-formations are conspicuous. In the basal portion of the stratigraphy is to be found the last of the gold-bearing, pyritic, quartz-pebble conglomerates. Above the dolomites, no further such horizons have been recorded, and red-bed lithologies make their appearance, continuing up into the Waterberg Sequence. In some of the goldfields, the Transvaal rocks rest directly on Witwatersrand strata, with no intervening Ventersdorp volcanics. The Transvaal depositional axis was shifted still farther to the northwest, relative to those of the earlier depositories.

The youngest of the Precambrian assemblages is the Waterberg Sequence which, so far, has proved barren of any significant gold mineralization. Its depo-axis is located farther, again, to the northwest of the Transvaal axis, and the cumulative shift in the successively-younger depositories has resulted in the Waterberg Basin's lying too far to the north for its members to be in contact with Witwatersrand formations anywhere within the latter depository. There is no preserved evidence of post-Waterberg, Precambrian basins on the Kaapvaal Craton, and there is an hiatus of the order of one billion years between the end of Waterberg deposition and the onset of Karoo sedimentation in the Devonian.

Between Waterberg and Transvaal times, the Kaapvaal Craton witnessed the intrusion of the impressive Bushveld Complex. The earliest members of this extensive pile of basic and felsic igneous rocks have an age of 2050 Ma. The Witwatersrand, Ventersdorp, and Transvaal sequences, thus, accumulated over a period of about 1100 Ma, between the development of the Archean granite-greenstone 'basement' and the emplacement of the Bushveld Complex and stretching from the Late-Archean to the Middle-Proterozoic. The Bushveld Complex is confined within the northeastern portion of the Transvaal depository and does not transgress onto either Ventersdorp or Witwatersrand rocks, except, possibly, at the presently-assumed eastern extremity of the Rand Basin.

The Nature of the Mineralization

Of a total accumulation of 11,000 metres of sediments and volcanics in the Witwatersrand Basin, the mineralized horizons have an aggregate thickness of 400 metres, equivalent to less than 4 percent of the stratigraphic column. Eighty percent of such horizons are located within the Central Rand Group, in the upper segment of the sequence, and, from these, 98 percent of the total amount of gold has been recovered (Table 7). It is obvious that a peculiar set of circumstances prevailed in the greying years of the basin's life, which were only hinted at in the formative years of the Dominion Group and in the maturing years of the West Rand Group. Any attempt to explain the Rand ore-deposits has to account for the restriction of significant mineralization to only a portion of the basin's history.

The original 'ground-truth' that the gold in the sediments was to be found, almost exclusively, in pyritic, quartz-pebble conglomerates has been dispelled, and, today, five different types of reefs, in the mining, not the sedimentological, sense of the word, are recognized as being capable of hosting economically-exploitable concentrations of gold and uranium (Table 8). Mainly as a consequence of the application of systematic, quantitative sedimentology, which was initiated at the beginning of the 1960's and which represents one of

TABLE 7

THE NUMBER OF EXPLOITED REEF-HORIZONS IN THE WITWATERSRAND BASIN

	No. of Reefs Mined	Percentage of WWR Total
Transvaal Sequence	1	-
Central Rand Group	16	80
West Rand Group	3	15
Dominion Group	1	5
Witwatersrand Sequence	20	100

the revolutionary milestones in the acquisition of data critical to the advancement of knowledge and understanding of the Witwatersrand Basin and its ore-deposits, the preferential sites of localization of heavy minerals within these different reefs have been identified (Table 9).

TABLE 8

TYPES OF EXPLOITED WITWATERSRAND REEFS

stratiform horizons containing gold and uraninite :

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

TABLE 9

PREFERENTIAL SITES OF LOCALIZATION OF GOLD IN WITWATERSRAND CONGLOMERATES

localization of gold and other heavy minerals within conglomerate horizon	: on scour surfaces, with pebble-lags
	: on lag surfaces
	: on winnowed surfaces
	: on crossbedding foresets
	: on tangential toes of foresets
	: on planar bedding surfaces
	: embedded in kerogen ('carbon seams')
higher concentration of gold in conglomerate horizon	: on bottom contact = lowest surface of degradation
	: on top contact = topmost winnowed surface
	: the more surfaces per vertical metre, the more gold

Based largely on the work of Hallbauer (1986), supplemented by observations by Feather and Koen (1975) and Feather and Glatthaar (1987), a broad summary has been abstracted of the characteristics of the gold particles in the conglomerates and other reefs (Table 10). Of particular relevance to the debate on the genesis of the metal is its mercury content and its fine grain-size.

TABLE 10

CHARACTERISTICS OF GOLD PARTICLES IN WITWATERSRAND CONGLOMERATES

percentage composition	:	Au 65-98 Hg 0,5-4,5 Ag 1-35 Zn 0,1-0,5
average grain-size	:	0,05-0,5 mm
	:	particles >2,5 mm very rare
	:	coarse particles more frequently associated with sulfides
	:	finer particles more frequently associated with quartz and phyllosilicates
primary (?) gold	:	rare inclusions in detrital (?) pyrite particles
	:	occasional, ovoid, nugget-like particles
secondary gold	:	closely associated with large variety of sulfides
	:	closely associated with kerogen ('carbon')

In addition to the gold, any explanation of the genesis of the mineralized horizons also has to consider the presence of pyrite, uraninite, brannerite, zircon, chromite, leucoxene, and the platinum-group metals, as the more important among 70 ore-minerals which have been observed. Of these, pyrite is the most abundant and, by volume, averages about three percent of the composition of the conglomerates. Hallbauer (1986) has recognized five main varieties :

1. allogenic, detrital pyrite within the size-range 0,06-5mm, constituting 30-70 percent of the total pyrite present in a particular sample;
2. syn-sedimentary pyrite, with an appreciable gold-content; 0,1-20mm; 10-15 percent;
3. pyrite pseudomorphs and replacements, particularly of chert and shale pebbles; less than 10 percent;
4. authigenic, post-sedimentation pyrite, a product of diagenesis and metamorphism; 0,01-2mm; 5-40 percent; and
5. late-hydrothermal and pseudo-hydrothermal pyrite, in secondary veins; less than 10 percent.

All types are not necessarily present together. In shape, the pyrite can be crystalline, rounded, oolitic, or framboidal (Hallbauer and Barton, 1987).

The uraninite grains generally have a grain-size of between 0,075 and 0,1mm, when they occur as discrete particles in the matrix of the reef (Hallbauer, 1986). More frequently, uraninite is associated with 'carbon seams', in which it has been altered to an uraniferous kerogen. Other common alteration-products are brannerite and uraniferous leucoxene (Feather and Glatthaar, 1987).

Zircon, chromite, and the platinum group-metals are conceded by all investigators to be of detrital origin. Koen (1961) was convinced that the uraninite, the zircon, and the chromite grains were in hydraulic equilibrium. Viljoen (1963) concluded that hydraulic equivalence also could be observed between zircon and pyrite. In considering the grammes/tonne concentrations, Minter et al. (1986) established linear ratios between zircon and gold, zircon and uraninite, and gold and uraninite.

Another controversial component of the reefs is 'carbon', often highly auriferous and uraniferous. The carbonaceous material is, in fact, kerogen, and it occurs in two forms : (a) as spherical particles, the so-called 'flyspeck carbon', 0,2-1,0mm in size, dispersed through the matrix of the reef, and (b) as layers, up to 4cm thick, on unconformity-planes and scour-surfaces. The thin, well-sorted, laterally-extensive and -persistent conglomerates, which are characteristically developed on conspicuous unconformities, usually contain a 'carbon seam' which contributes to the richness of such reefs, thereby making them the first-rank ore-bodies of the Witwatersrand Basin.

The Question of Genesis

The controversy on the origin of the gold strutted onto the stage of Witwatersrand geology within a year of the discovery of the first payable conglomerates, and, 100 years later, the "continued difference of opinion" is still alive and well and living in the minds of a good many of the researchers, both indigenous and exotic, who, once having drunk of the white waters, keep being drawn back, again and again, to the golden shore. In its simplest, but, alas, misleading, form, the dispute revolves around syngeneticism versus epigeneticism : was the gold introduced into the conglomerates at the same time as each reef was being deposited, or was it emplaced as a response to a later, quite-independent phenomenon, after all sedimentation of the basin had ceased? While mining engineers dominated the early development of the Rand, it mattered little where the gold came from and how it got where it was. It was there, and, as long as it remained predictably payable, that was all that mattered. But, as the geological community grew, so did the questions as to the source of the gold and the genesis of the reefs, and, with the questions, the disagreements, the disputes, and the divisions. As the years progressed, arguments arose about the uraninite, the pyrite, and the 'carbon', as well, and the gladiators found that the beast in the arena had transformed itself from a mono- to a quadrocerotic dragon.

Two factions evolved in the syngenetic school : (a) the placerists who believed that the gold and other heavy minerals had been washed into the basin by fluvial agencies and had settled out together with the sand and the pebbles; and (b) the precipitationists who subscribed to the idea that fluvial and sea-waters had contained dissolved gold and uranium, that such aqueous solutions had saturated the clastics, and that the metals had been precipitated coevally with the accumulation of the sands and gravels. Among the placerists, opinion was divided as to the origin of the pyrite. Some thought it was the product of black sands, such as normally found in modern-day alluvial deposits, which had been sulphidized, during either diagenesis or subsequent metamorphism. Others considered the pyrite to have been transported and deposited as detrital pyrite, this being possible because of prevailing anoxygenic conditions and a cold climatic environment. The classic placerist school had to convert to the modified-placer theory, to account for the crystalline, not water-worn, habit of the gold particles, the variety and paragenesis of the several sulphides in the matrices of the reefs, and the relation between uraninite and carbonaceous matter. Metamorphosis was ascribed to thermal fluids, of unknown origin, which dissolved the detrital constituents and reprecipitated them virtually *in situ*.

The epigeneticists also were divided into two camps. Both firmly believed that the gold and other ore-minerals had been deposited from hydrothermal fluids, which had selected the conglomerates as preferential channelways for extensive lateral migration, because of their relatively-high permeability, as opposed to the quartzites and shales of the hanging- and footwalls. The split came over the source of the hydrothermal fluids. Certain supporters held to the idea that the fluids were of magmatic origin and had been a product of either Ventersdorp or Bushveld igneous activity. Another element favoured the fluids as having been derived from metamorphic dehydration of the substantial volumes of argillites in the lower part of the Witwatersrand stratigraphic succession.

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

The Fields of Study

Attempts to resolve the enigmatic genesis of the gold and uranium mineralization in the Witwatersrand Basin have followed a maze of paths which have wound their ways through virtually all fields of geology. Despite the very-considerable effort which has been made over 100 years of observation, interpretation, and speculation, no single, unequivocal clue has emerged, which offers promise of laying the controversies to rest. In preparing this review, only a small proportion of the voluminous literature on the Witwatersrand and its ore-deposits has been included in the list of references quoted. The choice has been subjectively selective, and the fact is acknowledged that a not-insignificant number of other publications of, at least, equal merit deserve consideration in outlining the range of knowledge and argument that has been displayed in the arena.

In recording the progress of thinking on the Witwatersrand and in offering a forum for discussion, the Geological Society of South Africa can be credited with major achievements through the following publications, all of which are essential reading for an appreciation of the milestones that have been reached, and passed, in the Witwatersrand saga :

1931 - A Discussion on the Origin of Gold in the Witwatersrand System

1964 - The Geology of Some Ore Deposits in Southern Africa, Vol. I
(S.H. Haughton, ed.)

1986 - Mineral Deposits of Southern Africa, Vol. I
(C.R. Anhaeusser and S. Maske, eds.)

1986 - Geocongress '86 : Extended Abstracts

Two notable contributions have emanated also from the United States Geological Survey and the International Atomic Energy Agency, respectively :

1981 - Genesis of Uranium- and Gold-Bearing Precambrian Quartz-Pebble Conglomerates (F.C. Armstrong, ed.)

1987 - Uranium Deposits in Proterozoic Quartz-Pebble Conglomerates (D.A. Pretorius, comp.)

What has been assembled in these six *vade-mecums* stretches across all the fields of study for which additional, selected, specific references are indicated below.

Syntheses and Reviews

The episodic, but prodigious, outflow of data from mining, exploration, and research activities has encouraged, and necessitated, frequent attempts to consolidate all facets of Witwatersrand geology, with the objective of assessing whether the whole picture might be more informative than the separate parts. Both syntheses and critical reviews have presented the evidence for, and the arguments for and against, the several factions of each of the schools of thought concerning the genesis of the mineralization. Publications in this category, from which the substance of the present review has been drawn, include, in chronological order : Ballot (1888), Hatch and Chalmers (1895), De Launay (1896), Becker (1897), Denny (1897), Hatch (1898), Mellor (1915, 1916), Horwood (1917), Du Toit (1954), Brock and Pretorius (1964a and b), Pretorius (1966, 1975, 1976b, 1981), Haughton (1969), Tankard et al. (1982), Skinner and Merewether (1986), Boyle (1987), Hallbauer and Barton (1987), and Robb (1987).

Petrology, Mineralogy, and Geochemistry

From the very beginnings of geological studies of the Witwatersrand, great weight has been placed on the compositions of the ore-minerals and the host-rocks. It was considered that within the gold particles, the sulphides, and the other heavy minerals, as within the pebbles and matrices of the conglomerates and associated clastic sediments, would be found the evidence that would settle the disputes concerning the origins of the mineralization. However, it was soon appreciated that the ore-bearing formations had suffered pervasive, post-depositional alteration and that the search for pristine constituents would be fruitless. The recognition of the effects of such alteration spurred petrological investigations into the signatures of metamorphic and diagenetic overprints. Mineralogical and geochemical studies were boosted to a marked degree by the realization in the 1940's and 1950's that uranium was another exploitable element among the more than seventy ore-minerals which have been identified. An aspect of the mineralogy that, during the 1960's, received increasing attention, as an adjunct to sedimentology, was the examination of the hydraulic equivalences of undisputed detrital components and the problematic ore-minerals. Fluid-inclusion and isotope-geochemistry studies are the most-recently adopted approaches. The following are the contributions to the petrology, mineralogy, and geochemistry of the Witwatersrand rocks and ores, which have been drawn upon : Hatch and Corstorphine (1904), Young (1917), Fisher (1939), Liebenberg (1955), Ramdohr (1958), Koen (1961), Viljoen (1963), Hiemstra (1968a and b), Feather and Koen (1975), Hirdes (1984), Hallbauer (1986), Feather and Glatthaar (1987), Phillips and Myers (1987), Reid et al. (1988), and Phillips (1988).

Sources and Processes of Mineralization

More diverse opinions have been expressed on these two topics than on all the other fields of study put together. In a substantial number of contributions, theory has overshadowed fact. For 70 years, conclusions regarding the genesis of the mineralization lent heavily on comparative geology : what was seen in the Witwatersrand was compared with classic examples of hydrothermal-gold lodes or placer deposits elsewhere in the world. The origin of the Witwatersrand was decided upon by the closeness to, or divergence from, the characteristics of such ore-bodies. Deduction was employed as the favoured process for resolving the discord. Induction rose into the ascendency only from the late-1950's onwards, when empirical geology, with its ever-increasing base and widening range of observation and quantification, displaced comparative geology. The summary of information and ideas in the present synthesis is based on the following sources, arranged chronologically : Louis (1886), Penning (1888), Dorsey (1889), Rathbone (1891), Halse (1893), Hatch (1895), Curtis (1908), Gregory (1908, 1909), Graton (1930), Mellor (1931), Garlick (1953), Miholic (1954), Davidson (1955, 1960, 1965), Liebenberg (1960), Reimer (1975, 1984), Pretorius (1976a and b, 1984a), Button and Tyler (1981), Clemmey (1981), Myers (1981), Hallbauer (1984), Hirdes (1984), Mossman and Dyer (1985), Robb and Meyer (1985, 1987a and b), Hallbauer et al. (1986), Klemd and Hallbauer (1987), Phillips et al. (1987), and Hutchinson and Viljoen (1988).

Geochronology

The age of the Witwatersrand assemblage of sediments and volcanics has always been a prime factor in trying to establish the place of this allegedly-unique mineralization within the world family of gold deposits. Early workers (Hatch and Chalmers, 1895) considered the formations to be of Lower-Devonian age and compared them to the Paleozoic accumulations of clastic sediments in the fold-mountains of the Cape Province, where the geology of South Africa was first studied. It was predicted that the gold deposits would peter out when the mines reached the Silurian. By the late 1900's, it was generally accepted that an Upper-Paleozoic age was unrealistic, and it was believed by the majority of geologists that the Witwatersrand was definitely Precambrian and probably equivalent to the Proterozoic Algonkian of North America (Gregory, 1909). There the matter rested until the 1960's and the advent of isotopic dating. In the past thirty years, a substantial number of papers has appeared, reporting the results of progressively-more sophisticated and reliable age-dating, and pushing the Witwatersrand farther and farther back towards the Archean. The following are offered as possibly the more-informative compilations of geochronological data and their interpretation : Nicolaysen et al. (1962), Van Niekerk and Burger (1964), Pretorius (1965), Reimer (1975), Allsopp and Welke (1986), Armstrong et al. (1986), Barton, Barton, et al. (1986), Barton, Roering, et al. (1986), and Robb et al. (1989).

Sedimentology

Despite the fact that no one among the investigators disputed that all the economic mineralization in the Witwatersrand Basin was hosted in clastic sediments and that all exploration for further gold-bearing reefs was based on the search for, and recognition of, quartz-pebble conglomerates and associated sediments, the application of sedimentology to attempting to solve the problems of the genesis of the mineralization remained sorely neglected for almost forty years. An indirect sedimentological parameter was first considered by

Gregory (1908) when he employed mine assay-plans to delineate quantitatively the distribution-patterns of richer and poorer zones within the reefs. Mellor (1916) also utilized this technique to define areal variations in the intensity of mineralization. But, it was the work of Reinecke (1927, 1930) on the pay-shoots of the East Rand Goldfield that first illustrated the value of recording and measuring sedimentary structures and textures, as supplements to value-distribution studies. Unfortunately, the exploration boom that started in the early 1930's diverted attention from the promise of applied sedimentology, and it was not until the beginning of the 1960's that systematic sedimentological investigations regained a role in the array of approaches to deciphering the origins of gold and uranium in the Witwatersrand Basin. The pioneering research of Steyn (1963) and Armstrong (1965) yielded such convincing proof of the value of sedimentology that a veritable flood of literature followed and still continues. Minter (1972, 1976a and b, 1988) has become the outstanding contributor in this field, but many, many other geologists have added to the vast repository of information on the processes and responses of sedimentation in the development of all varieties of reefs. Several of the references on syntheses and reviews of Witwatersrand geology, as well as the benchmark compilations of the Geological Society of South Africa, contain expansive accounts of sedimentological studies on both macro- and micro-scales.

Paleobiology

In less than ten years after the discovery of the gold-bearing conglomerates, the presence was observed of 'carbon' among the more-common constituents of the matrix. In certain reefs, it was conspicuous in its close association with gold. Consequently, epigeneticists indulged in a great deal of speculation upon the role of 'carbon' as a 'precipitator'. The discovery of new goldfields in the 1930's and 1940's brought to light the presence of extensive, exceedingly-rich 'carbon seams', and it was observed that uranium, too, was generally present in the carbonaceous material in unusual concentrations. The nature and origin of the 'carbon' remained problematical until the availability in the 1970's of ultra-high-powered microscopy and refined, organic-geochemical analysis. Snyman (1965) initiated examination of the morphology of the constituents of the carbonaceous material, and, thereafter, Hallbauer (1986) became the leading investigator in the field, together with different co-workers (Hallbauer and Van Warmelo, 1974). The most-detailed, organic-geochemical studies have been carried out by Zumberge et al. (1978). Among the more-recent contributions on the roles of cyanobacterial (algal) mats in the process of mineralization is that of Mossman and Dyer (1985).

Geological Structure

The structure of the Witwatersrand Basin and its possible influence on the distribution and localization of gold and uranium have received surprisingly-little attention. Structural features on individual mines and goldfields have been well documented, but it was not until the benchmark compilations of Borchers (1960, 1964) that a comprehensive structural map of the basin, as an entity, became available. On a regional scale, no attempts have been made by epigeneticists to identify a possible relation between post-depositional dislocations and the dispositions of ore-bodies. Sedimentological observations soon suggested an inter-connection between both folds and faults and the preferential development of certain reefs, and research was encouraged into the patterns of interference-folding, the development of domes and depressions, and the siting and geometry of goldfields (Pretorius, 1983, 1986a and b). The interpreted pene-contemporaneity of structural deformation, sedimentation, and mineralization emerged as a factor which had to be afforded prime importance in debating the genesis of the reefs. To celebrate the centenary of the discovery of the Witwatersrand, the Geological Society of South Africa published a new geological and structural map of the basin (Pretorius et al., 1986), the potential value of which still awaits assessment in the genesis dispute.

Tectonic Setting

In the debate between the syngeneticists and the epigeneticists, the dictum prevailed, for a good 90 years, that, the larger in scale the field of study, the less likely it was to provide evidence that could contribute to a resolution. Faith was placed in the micro-field of mineralogy, petrology, and geochemistry. The mega-fields of basin-geometry, regional structure, and tectonic setting were left to lie fallow. From the 1960's, there developed an ever-more-compelling need to delineate new exploration targets, as the gold-price took on a progressively-rosier hue, and 'big-picture' studies were more-favourably received. It was put forward that the unravelling of the time and place of the Witwatersrand story in the pageant of crustal evolution in Southern Africa might identify the overall environment in which the sediments accumulated and suggest the nature and the source of the fluids which had permeated the depository. Pretorius (1973, 1984b, 1985) explored the possibility of an intracontinental setting on a stable craton and compared the location, geometry, and age of the basin with the parameters of other Precambrian sedimentary-volcanic assemblages in the geologically-older segments of Southern Africa. Van Biljon (1980) was the first to propose that the Witwatersrand might be better accommodated within a plate-tectonic setting, a theme which has been advanced persuasively by Burke et al. (1985, 1986) and Winter (1987). The gamut of mineralizing processes associated with crustal evolution by plate tectonics offers a fertile field in which to re-think the genesis of Witwatersrand gold and uranium.

The Genesis of the Mineralization

Chapters in Witwatersrand Thinking

In tracing the development of thought on the genesis of gold, uranium, pyrite, and other problematic components of the conglomerates, pyritic quartzites, unconformity surfaces, and 'carbon seams', five, broad periods of argument and counter-argument can be recognized as belonging to the prime chapters in the history of exploration, development, and exploitation of the Witwatersrand goldfields :

I. 1886-1900 : the first period of prospecting, discovery, and development

II. 1901-1932 : a period of consolidation — deep-level mining in the Central Rand and West Rand goldfields; the exploitation of the East Rand goldfield

III. 1933-1960 : the second period of exploration, discovery, and development — the resuscitation of the Witwatersrand mining industry by South Africa's going off the gold-standard; the advent of geophysical prospecting; the discovery of the

Carletonville, Klerksdorp, Welkom, and Evander goldfields; the doubling of the known extent of the basin; the recovery of uranium

IV. 1961-1981 : a period of consolidation — the fading of the older Central, East, and West Rand goldfields; the ascendancy of the newer goldfields; ultra-deep-level mining in the Central Rand and Carletonville goldfields

V. 1982- ? : the third period of exploration, without discovery, as of 1988 — the stimulus of an enhanced gold-price; the search for new concepts, strategies, and tactics of exploration as antidotes to the giddily-high cost of search and the soberingly-low rate of success in finding new goldfields

In their review, delivered at the Centenary celebrations of the discovery of the Witwatersrand goldfields, of the genesis of the ores, Skinner and Merewether (1986) classified the plethora of postulates on the origin of the gold into three, prime categories :

1. paleoplacer, in which the gold was introduced into the conglomerates and other sediments as detrital particles;
2. syngenetic, in which the gold was precipitated from a solute complex in surface waters; and
3. epigenetic, in which the gold entered the host-sediments in hydrothermal solutions that ascended through porous clastics.

The paleoplacer interpretation was first known as the alluvial theory, while a syngenetic origin was termed the precipitation theory. The epigenetic concept first was mooted as the infiltration and impregnation hypotheses, becoming known as the hydrothermal theory from about the 1920's onwards.

The Period 1886-1900

The majority of the earliest investigators favoured the alluvial theory, but their arguments had two vulnerable facets, which the infiltrationists exploited progressively, to bring more and more converts into the epigenetic school. The placerists could not explain adequately the fine grain-size of the gold particles and their irregular, hackly shape. With rounded, water-worn nuggets virtually absent from the conglomerates, the alluvial school enjoyed but a short period of dominance. In 1893, the placerists started their counter-attack by introducing the re-dissolved-placer theory, subsequently to be known as the modified-placer theory, which claimed that, at some time after the washing in of the detrital gold particles, they were dissolved in circulating, hot fluids and re-precipitated *in situ*. The infiltrationists immediately wanted to know why a two-stage process was necessary to produce a final product that complied with all the diagnostic features of a single process. That question is still being asked today.

Up to 1900, the three schools had the following as their chief spokesmen :

alluvial theory : Cohen (1887), Ballot (1888), Becker (1897), and Denny (1897)

infiltration theory : Louis (1886), Dorsey (1889), and Hatch (1895)

precipitation theory : Penning (1888), Rathbone (1891), and De Launay (1896)

The reconstitution of the gold was first suggested by Halse (1893), amplified and expanded by Becker (1897), and supported by Denny (1897). After 1900, the alluvial theory became the placer postulate and always carried with it the implication of post-depositional modification. The explanations for the origin of the gold, which were subscribed to by these pioneer students of the Witwatersrand, have been summarized in Table 11.

TABLE 11

THEORIES PROPOSED PRIOR TO 1900 FOR THE GENESIS OF GOLD IN THE WITWATERSRAND REEFS

syngenetic origin	:	1. placer (alluvial) theory: 1887 gold from unspecified external source 2. precipitation theory (a) gold from sea-water: 1888 (b) gold from thermal springs on sea-bottom: 1891
epigenetic origin	:	3. hydrothermal (infiltration) theory (a) gold from fluids from unspecified magmatic source: 1886 (b) gold from fluids associated with basic dykes: 1889 4. sublimation theory: 1890 gold 'sublimed in the form of vapour'
compromise	:	5. modified (redissolved) placer theory: 1893 detrital gold dissolved in thermal fluids and redeposited *in situ*

The Period 1901-1932

By 1902, the hydrothermal theory had become generally accepted as the most plausible of the hypotheses on the processes responsible for the introduction of gold into the conglomerates and the banded pyritic quartzites. The voices of the precipitationists had been stilled by 1904. The adherents of the modified-placer theory started, in 1908, another campaign against the epigeneticists, and, by 1915, the infiltrationists were in retreat, remaining so until the bitter battles of the 'Graton Challenge' at the end of the 1920's. The leading proponents of the two prevalent schools-of-thought during the period 1901-1932 were :

for the modified-placer theory : Gregory (1908, 1909), Mellor (1915, 1916, 1931), Young (1917), and Reinecke (1927, 1930)

for the hydrothermal theory : Hatch and Corstorphine (1904, 1905), Curtis (1908), Horwood (1917), and Graton (1930)

Until the appearance of L.C. Graton in 1928, there was a gentlemanly air between the disputants. They agreed to disagree. But, Graton's (1930) treatise became a red rag to a rage of rabid rebutters. The degree of polarity between the two schools can be seen in the equally-emphatic statements of Mellor (1916) and Graton (1930). The former wrote : "The theory of infiltration from any outside source of supply demands so extended a series of purely hypothetical steps uninterrupted by any solid ground of observation and of demonstrable fact, that any one may be pardoned who comes to regard the further pursuit of an explanation in this direction as demanding a greater exercise of the imagination than is usually allowed in geological speculation". Graton (1930) countered by proclaiming that : "..... syngenetic accumulation of detrital gold within the reef gravels is so highly improbable and so unlike any of the determining conditions under which gold placer deposits have been formed that the detrital hypothesis for the Rand deposits cannot be accepted... the facts are compatible from beginning to end with the view that the gold has been introduced from a deep-seated magmatic source by hydrothermal solutions of the same kind as have produced many of the other great gold deposits of the world". The hackles of the placerists were raised also by their seeing Graton (1930) as playing the role of a shepherd trying to bring a flock of errant sheep back into the safety of the conventional fold, when he gave forth that he had come to steer the gold deposits of the Witwatersrand "..... permanently into the safe haven of this great genetic (hydrothermal) group".

In Mellor's (1916) condemnation is revealed the nub of the acrimony between the placerists and the hydrothermalists. The ranks of the former were composed essentially of resident geologists on the goldfields, who based their conclusions on years of day-to-day observation and hands-on contact with all the nuances of the sediments and their contained mineralization. The chief bearers of the epigenetic standard were short-term visitors, with consequent, limited, first-hand knowledge of the rocks, who argued from a base of comparative geology, while testing the goodness-of-fit between the Witwatersrand mineralization and the major gold-bearing ore-bodies elsewhere in the world. The placer school attached a label of uniqueness to the Rand and disclaimed the validity of comparisons. Unfortunately, Graton (1930) published only the first half of his monograph, in which theoretical and comparative arguments were accentuated; the second, in which it was intended that the evidence for his hydrothermal interpretations would appear, never saw the light of day, much to the chagrin of his opponents who brought the 1901-1932 period to a close with their concatenation of declamation and indignation in the Geological Society of South Africa's 1931 assemblage of answers to Graton's (1930) questioning of the basic tenets of placerism.

The modified-placer theory had received a powerful boost through the first, detailed, mineralogical and petrological examination of the Witwatersrand reefs, the results of which were reported in Young's (1917) benchmark addition to the Witwatersrand story. He substantiated many of the ideas first set out comprehensively by Gregory (1908) and came to the conclusion that the reefs represented marine gravels that had been deposited near the mouth of a large river and in which the allogenic gold and iron oxides had suffered subsequent solution, with re-precipitation of the gold. The iron oxides, in the original form of black sands, had been converted to pyrite by sulphuretted waters, the sulphidation being accompanied by the formation of rutile. At a still-later stage, there was further solution and re-precipitation of some of the pyrite, so that three generations of this important component of the reefs could be identified. Young (1917) also believed that certain of the other metallic sulphides, as well as chlorite, sericite, calcite, and carbonaceous matter, were derived from the proliferation of dykes during their cooling and subsequent alteration.

The dykes had been invoked as suppliers of mineralization by the hydrothermalists, so that, again, the question was asked : was it necessary to presuppose two stages of mineral-formation in order to end up with a product indistinguishable from that which could result from a single episode of infiltration into the conglomerates? As far back as 1895, Kuntz had proposed that the hot, mineralizing solutions which had permeated the conglomerates had been associated with the dykes which had intruded the sediments well after they had been deposited. Horwood (1917) became the leading proponent of the critical roles of dykes in the process of hydrothermal mineralization, claiming that "..... the dyke intrusions ..... opened deep-seated communications whence the mineralizers have ascended". From the solutions emanating from the dykes, gold, pyrite, and 'carbon' were precipitated simultaneously. It was considered that the persistent, longitudinal, diabase dykes were of most importance, and that such intrusions were associated with the outpouring of the Ventersdorp lavas. Other than for this postulate, the hydrothermalists remained silent with respect to the source of the mineralizing fluids. Graton (1930) mentioned casually "a deep-seated magmatic source" and delved no further into this component of the epigenetic hypothesis.

As much as the hydrothermalists were vague as to the source of the mineralizing fluids, so, too, did the placerists shy away from offering opinions on the provenance of the detrital gold and pyrite. The proto-sedimentological studies of Mellor (1915, 1916) and Reinecke (1927, 1930) pointed to a source-area to the northwest of the basin, where, it was hinted, but not positively proclaimed, "basement" rocks, similar to those of the "ancient schist belts" had housed typical quartz-vein, lode-gold deposits. The epigenetic school queried such an assumption on the grounds that the abundant quartz pebbles of the conglomerates were conspicuously and consistently devoid of any signs of primary gold mineralization. In all their debating, the adherents of neither school undertook to look beyond the narrow limits of the goldfields for evidence that might help resolve their differences.

What fanned the flames of the placerists' harangue against Graton's (1930) treatise, extolling the "truth" revealed by the hydrothermal theory, was his perfunctory disregard of the substantial volume of evidence which had been gathered by Gregory (1908), Mellor (1915, 1916), Reinecke (1927, 1930), among many others, as to the distribution-patterns of gold assay-values in the reefs and the close relation between such patterns and the more-prominent sedimentary features of these host-rocks. Gregory (1908) was impressed by the "magnificent mine plans, whereon are tabulated the results of years of observations .....". By Reinecke's (1930) time, the information available from the assay-plans had reached almost unmanageable proportions, but, yet, it could be seen clearly that the mineralization-patterns bore no correlation with faults, dykes, or other post-depositional features. The more-robust reefs were revealed to be confined to channels in the sediments, and the zones of enhanced gold-values reflected physical reworking by winnowing and scouring. To the placerists, this was convincing proof that the gold was of alluvial origins. So, they reacted strongly against Graton (1930) when he commented on their evidence to the effect "..... that the occurrence of the gold is intimately related to the sedimentary characteristics of the conglomerates, receives invariable and powerful confirmation. But this relationship is found to exist not because the gold itself is sedimentary too, but because the gold has been deposited by solutions which were guided to the plane of deposition in the inter-pebble voids by permeability conditions that in turn depended directly on the sedimentary character of the conglomerates".

The 'Graton Challenge', short-lived as it might have been between 1928 and 1932, led to a rejuvenation of thinking on the Witwatersrand problem through the baiting of the placerists into rising up and advancing on all fronts to keep their banner flying high and victorious on the Ridge of White Waters. Skinner and Merewether (1986) succinctly summed up the role of L.C. Graton in the progression of the Witwatersrand story : "Graton was a polemicist and his polemics caused a backlash that spurred a generation of insightful work".

The Period 1933-1960

South Africa's departure from the gold-standard initiated an exploration boom that nurtured a total re-thinking of Witwatersrand geology and mineralization. New goldfields were found, new stratigraphic horizons with highly-payable reefs were recognized, new types of mineralization were identified, and another component of the reefs - uranium - demanded an explanation of its genesis. Virtually all previously-formulated concepts were re-examined. The precipitation theory was revived, the hydrothermalists added a worthy successor to Graton, and mineralogists ascended the podium as the main spokesmen for the modified-placer school. The following investigators can be singled out as leading the continued debate during the years between 1933 and 1960 :

for the modified-placer theory	:	Liebenberg (1955, 1960) and Ramdohr (1958)
for the hydrothermal theory	:	Fisher (1939) and Davidson (1955, 1960)
for the precipitation theory	:	Garlick (1953) and Miholic (1954)

In the same way as gold and pyrite served as the bones of contention in the first and second chapters of the Witwatersrand story, so uranium and 'carbon' constituted the battle-grounds of the third chapter. Liebenberg (1955), after an exhaustive study of the mineralogy of the uranium ores in all the exploited reefs, both old and new, proclaimed his firm conviction that the uraninite, in its original form, had been a detrital component, from which were derived several radioactive alteration-products. The 'carbon' he considered to be thucholite, consisting of "a heterogeneous mixture of hydrocarbon, detrital uraninite, secondary uraninite and other non-radioactive constituents". The conclusion was offered that the solid hydrocarbon had been formed by the irradiation of gaseous or liquid hydrocarbons by detrital uraninite. He recorded substantial evidence for a general, sympathetic relation between the gold- and uranium-contents, which feature of the various conglomerates and other reefs he believed indicated that "..... the gold and uraninite were deposited simultaneously and that whatever origin applies to the one must necessarily also apply to the other ..... the uraninite is detrital and the gold, notwithstanding its present form, must thus also be of detrital origin".

Ramdohr's (1958) mineralogical investigations also led him to subscribe to the placer school, but his convictions were somewhat less firm than Liebenberg's (1955, 1960), and he qualified his allegiance by stating that "..... none of the 'classic' hypotheses even approaches a satisfactory solution without either assuming complicated conditions or making hypothetical assumptions that are unrealistic". Though his mineralogical studies left him a hydrothermalist, Fisher (1939) also voiced his reservations about striding too confidently into any one particular camp by writing : "All the microscopic evidence is in accordance with the view that the gold was introduced hydrothermally but it can be reconciled fairly satisfactorily with the assumptions of the modified placer theory, which apparently accounts best for the geological data".

Attempts to explain the role of carbonaceous matter in the mineralizing processes also encouraged the re-appearance of the precipitation school. As one proponent, Mihalic (1954) put forward that the conglomerates were marine-shore deposits on which a rich vegetation of uranium-concentrating organisms had developed, thus being one of the earlier believers in a biogenic origin of the 'thucholite'. Natural waters, at the time the Witwatersrand sediments were laid down, contained high concentrations of uranium which was extracted by the organisms under anaerobic conditions that favoured the formation of pyrite from deeper, hydrogen-sulphide-bearing waters. At some later stage, "thermal waters containing gold in ionic form" passed through the uraniferous, carbonaceous material, and the gold ions were reduced to metal by the organic matter, in which the gold accumulated.

The 'Davidson Incursion' disputed the placerists' assumption that uraninite could withstand transportation in a fluvial system and called into question a further assumption that an anoxygenic environment prevailed, in which uraninite could survive as a detrital component of the gravels. Davidson (1955, 1960) doubted whether 'thucholite', because of its chemical instability, could have been concentrated in a placer formation and argued that it must have been introduced post-depositionally, at the same time as the gold in hydrothermal solution. He suggested that the 'carbon' represented carburan which had been polymerized radiogenically from methane and other hydrocarbon gases and fluids. Because of the low titania content, he could not accept that the pyrite had been formed by the sulphidation of detrital black sands, and, therefore, believed that the pyrite and other sulphides were products of the same hydrothermal fluids which were responsible for the gold. Charles Davidson, as had earlier hydrothermalists, used comparative geology as a broadsword in flailing away at the opposition, while his counter-attackers drew attention to the relative paucity of observational geology in his arguments. What he had seen elsewhere was of greater import than what he gleaned from looking directly at the Witwatersrand rocks. Nevertheless, Davidson was a contributor of stature to the debates on the genesis of the gold and uranium deposits and served as a vital stimulator of discussion over a period of 15 years. He was a Scotch terrier, snapping at the heels of the increasingly-irritated walkers along the shingly shore of syngeneticism. In 1960, Davidson delighted in claiming that "..... the epigenetic irritant implanted within the Witwatersrand oyster has in the course of time given rise to the pearl of truth .....".

The Period 1961-1981

By the beginning of the 1960's, successful exploration, with respect to the finding of new goldfields, was in a decline, and geological thinking was being turned more and more towards defining the controlling parameters of the new mineralization that had been found during the second, great period of prospecting. The twenty years that ensued saw sedimentology ascend to the throne and become monarch of all that was surveyed. A volume of geological data was generated, the likes of which had not been seen previously on the Witwatersrand stage, and the conclusions that emanated from this information were overwhelmingly in favour of the placer school. Among the more prominent advocates of the different hypotheses between 1961 and 1981 were :

for the modified-placer theory : Koen (1961), Steyn (1963), Viljoen (1963), Brock and Pretorius (1964b), Armstrong (1965), Pretorius (1966, 1975, 1976a and b, 1981), Hiemstra (1968a and b), Minter (1972, 1976a and b), and Feather and Koen (1975) for the hydrothermal theory : Davidson (1965)

for the precipitation theory : Reimer (1975) and Myers (1981)

Davidson (1965) tenaciously persevered with his campaign and published, as his swan-song, a comprehensive summary of his previous arguments, adding a novel suggestion as to the source of the mineralizing fluids. Instead of subscribing to ascending thermal solutions, derived from some unspecified, deep, magmatic source, as most of his predecessors had done, he envisaged that downward-percolating, hydrothermal fluids had selected certain, more-permeable, conglomerate horizons along which to spread laterally. Gold and uranium had been leached from the Ventersdorp volcanics by hot, saline waters, to form the first-rank reefs of the upper portion of the Witwatersrand stratigraphic succession, and from the Dominion volcanics, to mineralize the conglomerates in the lower portions. This proposal brought forth louder howls of protest than anything which Davidson had proffered previously.

A variation on the precipitation theme was contributed by Myers (1981). He accounted for the uraninite and the pyrite by viewing them as detrital constituents, while the gold had entered the reefs epigenetically in solution. This metal had been leached anoxygenically from sea-floor basalts and had been transported, complexed as aurous sulphide. The gold was precipitated by a reaction driven by the radioactive decay of detrital uraninite. The radiolysis of water had a mildly-oxidizing tendency which slowly dissolved the uranium, precipitated the gold, and oxygenated the 'thucholite'. In this manner, a uraninite placer on an unconformity was converted progressively to a gold reef, with little residual uraninite, and the most-mature reefs tended to grade towards the 'carbon-seam' type.

The placerists were given another string to their bow, when evidence was presented that the carbonaceous material was not the residue from gaseous or fluid hydrocarbons, but had had its origin in plant-like organisms. The morphological studies of Snyman (1965) and the organic-geochemical analyses of Zumberge et al. (1978) were the precursors of an array of investigations which led to the identification of the 'carbon seams' as the products of extensive, prokaryotic, microbial colonies. The 'carbon' was established to be, in fact, kerogen, representing the remains of cyanobacterial (algal) mats. The kerogen is an insoluble, random, aromatic polymer, with a high concentration of organic free radicals due to irradiation from radioactive elements within the coaly substance of the seams. Zumberge et al. (1978) reported that the carbon isotopes supported a biogenic origin. The distribution of the algal mats was shown to be associated with specific, sedimentological features in the reefs and adjacent clastics and with particular depositional facies. When integrated with gold- and uranium-value-distribution patterns and areal variations in other sedimentological parameters, the algal-mat facies yielded powerful support for sedimentary control on all types of reefs and mineralization, thereby strengthening the placerist argument.

Quantitative micro-sedimentology, undertaken in conjunction with the mineralogical investigations of the 1961-1981 period, suggested that uraninite, pyrite, and zircon were in hydraulic equilibrium, a relation which could be seen to apply also to the much-less-abundant arsenopyrite, cobaltite, and platinum-group metals (Koen, 1961; Viljoen, 1963). No doubt was expressed by any school as to the detrital origin of the zircon, and the placerists touted hydraulic equivalence as a nail in the coffin of the hydrothermalists. But, the latter countered by citing the fact that the modified-placer theory admitted that the original detrital gold, uraninite, and pyrite had been dissolved, re-precipitated, and reconstituted. Therefore, the grain-sizes measured for the hydraulic-equivalence interpretations did not reflect, necessarily, the parameters of the minerals at the time of deposition of the reefs. The epigenetic school also persistently drew attention to the observation of Feather and Koen (1975) that, of the more than 70 ore-minerals identified, a detrital origin could be ascribed convincingly to about 40 of these, and the question continued to be asked : if hydrothermal activity has to be invoked to explain almost half the ore-minerals, why could it not be credited with being responsible for all of them?

The sedimentological studies of this period produced revealing insights into the vertical and lateral distribution-patterns of the heavy minerals in the various types of reefs and defined, in considerable detail, the surfaces within the reefs on which the gold, uraninite, and pyrite had been concentrated preferentially (Minter, 1972, 1976a and b). The more surfaces there were per vertical metre of the conglomerate, the more gold there was present. Where crossbedding could be observed in the reef, gold particles, in some instances, could be seen as having cascaded down the foresets, with the grain-size diminishing progressively towards the toes. As Skinner and Merewether (1986) were later to remark, all protagonists in the dispute had to agree that, whatever the origin of the gold, uranium, and pyrite, the sedimentological characteristics of the reefs had played a major role in localizing the ore-constituents.

Following on the appearance of Borchers's (1960, 1964) maps, a start was made on the integration of sedimentology and structural geology into a basin-analysis approach to unravelling the location and nature of the provenance of the sediments and their contained ore-minerals (Brock and Pretorius, 1964a and b). Subsequent publications by Pretorius (1966, 1975, 1976a and b, 1981) reflected the majority opinion of the placerists that the gold had been derived from mafic and ultramafic members of Archean greenstone belts and the uranium from the enveloping and intruding granitic rocks of such terranes. The more-fertile source-areas were concluded to have lain to the west, northwest, and north of the present basin, a region which is covered now by a succession of post-Witwatersrand formations. Most of the deductions were made on the basis of the mineral assemblages in the reefs and of theoretical assumptions. The basin-analysts conceded that the detrital minerals derived from an Archean granite-greenstone environment all had been affected by later, aqueous fluids that had permeated the basin-fill. Geochronological data which became available, for the first time, during this period were used by the researchers into the 'big-picture' history of the Witwatersrand Basin to suggest that the hydrothermal fluids had been generated by Ventersdorp magmatism and the emplacement of the Bushveld Complex.

As the period 1961-1981 drew to a close, the first results appeared of attempts to gain a better understanding of the nature and condition of the provenance-rocks. Button and Tyler (1981) proposed that the sericitic arenites of the Witwatersrand Sequence, particularly of the upper section of the stratigraphy, had been derived from granitic paleosols, during the formation of which paleo-groundwaters had leached out uranium. It was assumed that conditions in the source-area favoured the prolonged development of a paleoregolith, the continued erosion of which supplied large volumes of coarse, clastic detritus to the basin. Such material could have moved across erosion-surfaces in the depository, "leaving behind no trace other than a lag of heavy and economically important minerals". The unconformities were the sites of significant changes in the heavy-mineral suites : the platinoids were leached of platinum, palladium, ruthenium; pyritization took place in the presence of reducing bisulphide-bearing groundwaters; sulphide complexation contributed to gold's going into solution; some of the mobilized gold was precipitated as rims round pyritized, chert pebbles. The uranium leached from the paleosols was carried into the conglomerates in solution, so that the formation of the reefs had to be seen as complying, in part, with the precipitation theory and, in part, with the placer theory.

Despite all the advances in knowledge and all the new approaches which had been followed up to the beginning of the 1980's, it had to be admitted that Du Toit's (1954) summing up of the dilemma still could not be refuted : "..... many of the arguments put forward on behalf of one of the two main rival theories can indeed, with but slight modification, be employed in favour of the other ..... it must candidly be admitted that the criteria available are not so obvious nor individually so convincing as to compel universal acceptation of any one view .....".

The Period 1982-1988

In 1982, the Witwatersrand geological community began to prepare itself for the commemoration, in 1986, of the centenary of the discovery of the goldfields. In that year, Pretorius (1984a) called for a much-more intensive look at the postulated source-terrane of the basin-fill and the mineralization it hosted. At the same time, the Geological Society of South Africa decided to commission a compendium of updated accounts of each of the goldfields and posted notice that it would be open-season for any contribution on any aspect of the Witwatersrand story. What ensued is a monumental testimony to what has been, and is being, done to resolve what Charles Davidson (1965) called "the most disputed issue in the history of economic geology" - the genesis of the Witwatersrand ores.

A summary of the main lines of thought that have emerged and have been pursued during the period termed the 'Centenary Dissection' of the body of Witwatersrand knowledge is presented later. The ideas that are commented on are drawn from the following spokesmen for the three schools :

for the modified-placer theory : Pretorius (1984a), Hallbauer (1984, 1986), Robb and Meyer (1985, 1987a), Robb (1987), Klemd and Hallbauer (1987), Hallbauer and Barton (1987), Feather and Glatthaar (1987), Minter (1988), and Hutchinson and Viljoen (1988)

for the hydrothermal theory : Phillips and Myers (1987), Phillips et al. (1987), and Phillips (1988)

for the precipitation theory : Reimer (1984) and Mossman and Dyer (1985)

Past Arguments : A Summary of 'a Continued Difference of Opinion'

In Table 12 has been prepared a chronological overview of the various concepts of ore-genesis, which have received the support of the majority of investigators from the discovery of the Witwatersrand in 1886 up to the Centenary Year in 1986. It fairly illustrates the conclusion of Skinner and Merewether (1986) that "..... while the modified placer theory is a clear leader, the other theories remain alive ..... the modified placer theory is extremely powerful".

Any attempt to summarize the vast array of arguments which have been brought forth by all the contestants is a daunting task of the first magnitude.

TABLE 12

MAJORITY OPINIONS OF THE GENESIS OF WITWATERSRAND GOLD MINERALIZATION 1886-1986

1886-1890	:	placer	:	Au - unspecified
1890-1910	:	hydrothermal	:	Au - basic dykes
1910-1932	:	modified placer	:	Au - Precambrian greenstones
1928-1932	:	the Graton Challenge	:	Au - 'deep-lying magmatic source'
1932-1951	:	modified placer	:	Au - Archean greenstones
1951-1965	:	the Davidson Incursion	:	Au and U - 'lixiviation' of Ventersdorp volcanics
1951-1986	:	modified placer	:	Au - Archean greenstones; U - Archean granites
1986- ?	:	the Centenary Dissection	:	a 'white-water' stretch of confirmation, refutation, recantation, and innovation

To select the ten, most-frequently-fired fowling-pieces in the arsenals of the antagonists also is fraught with formidable complexities. Nevertheless, Tables 13 and 14 are offered as highly-subjective condensations of the main deficiencies which the placerists and the hydrothermalists have focused on in each other's proclamations of 'truth revealed'. Many of the arguments which were in the forefront of the disputes at a particular period were exposed as fallacious in a later period. Time also showed that much of the alleged evidence, which had been based on observational geology, could not stand fast against the onslaught of sophisticated, quantitative data contributed by laboratory-studies. But, the ultimate weapon, essential to bringing the war to an end, still remains to be designed and deployed.

TABLE 13

MAIN ARGUMENTS ADVANCED AGAINST PLACER ORIGIN OF WITWATERSRAND MINERALIZATION

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

Graton's (1930) assessment of the sense of stalemate that hung over the battlefield more than fifty years ago still prevails : "If undoubted detrital grains of gold could actually be found either in the pyritic quartzite bands or in the conglomerate, and if these grains were found, even to the

TABLE 14

MAIN ARGUMENTS ADVANCED AGAINST HYDROTHERMAL ORIGIN OF WITWATERSRAND MINERALIZATION

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

smallest sizes discernible, to show entire immunity to the subsequent mineralizing processes, this ought to go far towards establishing the true degree of importance of detrital gold on the Rand. Until or unless such a discovery shall be made, I see no escape from a continued difference of opinion on this score. For no one can absolutely rule out the possibility of detrital gold, and on the other hand, I suppose some of us will never forego the belief that part of the gold is epigenetic".

Present Lines of Thought

As has been mentioned, the occasion of the centenary of the discovery of the Rand goldfields generated an overview of the Witwatersrand story of a proportion not previously witnessed. To adequately evaluate the impressive mass of new information that has become available and to integrate the many interpretations into new, more-refined models of the three genetic theories of the mineralization will require a decade of further analysis and synthesis. Only a cursory review can be offered now, in the early years of the 'Centenary Dissection', of the directions which are being followed in the present period of 'confirmation, refutation, recantation, and innovation'. Lines of thought are being explored; canticles of conviction are a long way from the singing thereof.

Tectonic Setting of the Basin

Although a preference still prevails for the development of the Witwatersrand Basin under extensional conditions in an intracratonic setting, an increasing number of the 'broad-brush' geologists are being attracted to the cratonic foreland-back arc framework of Burke et al. (1985, 1986) and Winter (1987). The relative strengths of arguments for sedimentary accumulation under back-arc conditions, in contrast to the previously-held concept of deposition in a cratonic, yoked basin, require assessment. Minimal thought has yet been given to the other components of a cratonic-foreland setting : the magmatic arc, the fore-arc basin, the trench or the suture. If the gold and uranium accumulated in a back-arc basin, then it has to be determined what manner of magmatic activity and what type of mineralizing processes in the arc could have yielded the exceptional volumes of these minerals that entered the basin, either as detrital particles or in hydrothermal solutions.

Age of the Witwatersrand

On the basis of the latest attempts (Robb et al., 1989) to establish an age for the formation of the Witwatersrand Basin, it has to be concluded that the sedimentary-volcanic assemblage now has to be regarded as Late-Archean, and not Early-Proterozoic. Previously, it had been believed firmly that Witwatersrand sedimentation was a response to Proterozoic-style crustal evolution and that it was markedly different to that characteristic of Archean-style greenstone belts (Pretorius, 1976a and b, 1981, 1983). This classification required that a Proterozoic, stable crust had evolved earlier in Southern Africa than in most other places in the world, and the alleged uniqueness of the Rand as a metallogenic province was ascribed, in part, to this unusually-early onset of the Proterozoic.

Robb et al. (1989) have put forward that the age of the Witwatersrand succession lies between 3105 and 2718 Ma. Internationally-accepted boundaries for the Late-Archean are regarded now as 2500 and 3000 Ma. The base of the Witwatersrand would extend, therefore, into the uppermost segment of the Middle-Archean (3000-3400 Ma). When the age of the Witwatersrand was considered to lie between 2700 and 2400 Ma (Pretorius, 1965), it was still conceivable that the assemblage might straddle the Archean-Proterozoic transition-line. As the minimum age of the sediments has been pushed back progressively, so has the difficulty increased of not regarding the basin as being of Archean age. The proposal that the depository might have been related to a magmatic arc, rather than to a stable craton, has helped resolve the problem of placing an assumed, Proterozoic-style basin in the Archean. Sedimentation in a back-arc environment, concurrently active with a fore-arc, Archean-style, volcano-sedimentary environment, could well resemble that characteristic of a Proterozoic, intra-continental regime.

In the first attempt to put age-constraints on the three main stratigraphic groups which constitute the Witwatersrand Sequence, Robb et al. (1989) have defined the following intervals in which basin-fill accumulated :

Central Rand Group	2895-2718 Ma	Upper Witwatersrand Division
West Rand Group	3038-2895 Ma	Lower Witwatersrand Division
Dominion Group	3105-3060 Ma	Basal Witwatersrand Division

In 1965, Pretorius intimated that there might be a 300-Ma periodicity in the evolution of what were then believed to be Proterozoic-style, sedimentary-volcanic basins on the Kaapvaal Craton, one of the old nuclei of Southern Africa. The development of the depositories took place between the following time-limits : Pongola Sequence (3000-2700 Ma); Witwatersrand Sequence (2700-2400 Ma); Ventersdorp Sequence (2400-2100 Ma); Transvaal Sequence (2100-1800 Ma); and Waterberg Sequence (1800-1500 Ma). A modification to a 250-Ma cyclicity and a shifting downwards of minimum ages was later introduced (Pretorius, 1976a), in which the Witwatersrand was shown as being confined between 2750 and 2500 Ma. With the many, new ages, of much-greater precision, which have been added in the past decade, it is now considered that a cyclicity of 350 Ma might better accommodate the span of basin-development on the Kaapvaal Craton. In this new classification, the Pongola Sequence would be removed as a discrete entity and would revert to its earlier correlation with the Witwatersrand assemblage, so that the basins now would be allocated the following time-boundaries, the Ventersdorp succession stretching across the Archean-Proterozoic transition :

Waterberg Sequence	: 2050-1700 Ma
Transvaal Sequence	: 2400-2050 Ma
Ventersdorp Sequence	: 2750-2400 Ma
Witwatersrand Sequence	: 3100-2750 Ma

The Witwatersrand strata show overprinting, reconstitution, and resetting, according to Armstrong et al. (1986) and Barton, Barton et al. (1986), at 2800 Ma, 2500 Ma (Ventersdorp imprint), 2350 Ma, 2200 Ma, and 2050 Ma (Bushveld imprint). There are, thus, at least, four occasions in post-Witwatersrand times, during which processes were active which could have led to the changes in the gold, pyrite, uraninite, and other mineral constituents of the reefs, the alteration called upon by the modified-placerists to explain away the presently-non-detrital habit of the ore-minerals.

Relatively large volumes of granitic material were generated from the lower crust at 2800 Ma, and, at the same time, there was pervasive, hydrothermal alteration of all the granitic rocks of the provenance-region to the northwest of the basin. A limited amount of evidence is available to show that this hydrothermal activity also affected the Dominion Group at the base of the Witwatersrand succession. What is believed to be highly relevant to attempts to decipher the genesis of the mineralization is the fact that this interlude of granite-emplacement and hydrothermal activity was coeval with the laying down of the Upper Division (Central Rand Group) of the Witwatersrand Sequence (Robb et al., 1989), which hosts 98 percent of the gold recovered. Whereas the hydrothermalists could not point to any major igneous or metasomatic activity in, or adjacent to, the basin in their long search for a source of the mineralizing fluids and had to resort to the effects of dyke-intrusion and Ventersdorp volcanism, the present-day school of placerists, in its recognition of the hydrothermally-altered granites, has given its adversaries a powerful, new missile with which to re-engage battle.

If, as would appear, the laying down of the more significant reef-horizons, the emplacement of mineralization, the intrusion of granitic material, and hydrothermal activity on a regional scale were pene-contemporaneous, then all three schools of thought might have to be called upon as contributing coequally and coevally to the generation of the ore-deposits. Such mineralization would have to be thought of now as falling within the time-range of another great class of gold-deposits — the Archean, greenstone-hosted lodes that, world-wide, are clustered in the 2500-2800-Ma metallogenic epoch (Hutchinson and Viljoen, 1988). The Witwatersrand could come to be regarded as the jewel in the golden crown of the Late-Archean, instead of as an oddity in the Early-Proterozoic.

A New Model of the Basin

The considerable mass of new information yielded by the exploration boom of the 1980's has necessitated a revised model of the depository to that outlined in Figure 1 and Table 5, the earlier model being based on the state of basin-analysis in the years immediately preceding the opening of the Centenary flood-gates. The geometry of the depository was re-examined by Pretorius (1986b), in the light of structural data emanating from many, recent boreholes, from the results of the first, systematic employment of seismic surveys, and from digital image-processing of the gravimetric and aeromagnetic fields over the basin and its surrounding terranes. An arrow-head shape, instead of an oval one, was defined (Figure 2), indicating that the central axis of the basin is represented by an anticline plunging northeastwards, and not by a syncline plunging south-westwards, explaining the large, uplifted region, apparently devoid of Witwatersrand rocks, which is situated to the southwest of the depository.

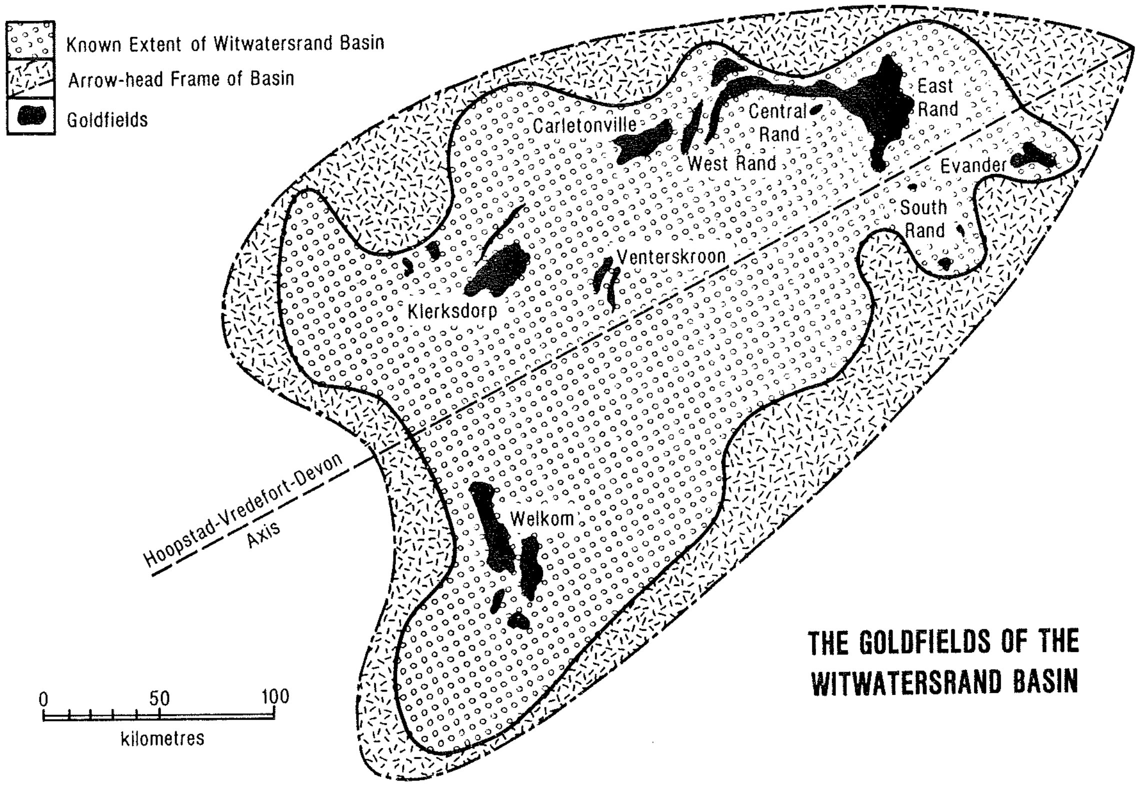

Figure 2 : *The arrow-head frame of the Witwatersrand Basin, symmetrical about the Hoopstad-Vredefort-Devon anticlinal axis. The Klerksdorp, Venterskroon, Carletonville, West Rand, Central Rand, and East Rand goldfields are contained within the flanking syncline to the northwest of the axis and the Welkom, South Rand, and Evander fields within another, separate syncline to the southeast of the axis.*

The definitive parameters are set out in Table 15. The dimensions have changed, in accord with the modified geometry, and a foreland back-arc environment is preferred, which implies the development of a magmatic arc in a provenance-region originally constituted by Middle-Archean granites and green-stones, similar to those which have been studied intensively in the Barberton Mountain Land of the Eastern-Transvaal sector of the Kaapvaal Craton. Comparison with new sedimentological criteria established in North America and Europe suggests that a goldfield has the characteristics of a braid-delta, rather than of a fluvial fan. The age of the basin is shown in the revised basin-analysis model of the Witwatersrand as 3000-2700 Ma, whereas the latest age-measurements, available since the second model was constructed, have led to a shift to 3100-2750 Ma. In either case, the Witwatersrand is now taken as belonging to the Late-Archean.

TABLE 15

BASIN ANALYSIS OF THE WITWATERSRAND DEPOSITORY : 1986-1988
SECOND MODEL OF DEFINITIVE PARAMETERS

Orientation of Basin	:	NE - 390 km; NW (max.) - 250 km; NW (min.) - 90 km
Shape of Basin	:	arrow-head; asymmetrical; deeper side on NW
Type of Basin	:	foreland back-arc
Development of Basin	:	lower division of sequence - alternatively expanding/shrinking
	:	upper division of sequence - progressively shrinking
Age of Basin	:	2700-3000 Ma (conventional L. Archean)
Provenance	:	penecontemporaneous L. Archean magmatic arc in M. Archean granite-greenstone basement
Nature of Goldfield	:	a distal braid-plain/braid-delta peripheral to a shallow lake

New Genetic Models

The concerted effort to assemble data for presentation at the Centenary commemoration produced several new hypotheses on the manner in which the gold-uranium mineralization was introduced and concentrated in the different types of reefs. The long-held idea that the gold had come from Archean greenstones and the uranium from associated granitic rocks still attracted the most support, but new variations on this theme helped to explain away some of the problems in the modified-placer theory, which the hydrothermalists have persistently underlined. The emphasis among the epigeneticists was directed towards the role of metamorphism in generating the mineralizing fluids. The precipitation advocates saw biogenic activity as important in both solution and precipitation.

Reimer (1984) submitted that the gold had been derived from the Archean greenstone belts, but added banded iron-formations to the previously-favoured mafic and ultramafic igneous rocks as primary hosts to the metal. Hirdes (1984) also mooted the iron-formations as, possibly, the most significant source-rocks. The gold was dissolved, during weathering, under the influence of cyanogenic micro-organisms and was transported as organic-protected colloids (Reimer, 1984). The distance of transport was considered to be not more than 30 km. Precipitation took place through the medium of organic matter, and this process was virtually contemporaneous with the deposition of the enclosing sediments. The precipitated grains were reworked mechanically, and mobilization and reprecipitation followed during later metamorphism. The gold in the 'carbon seams', according to Mossman and Dyer (1985), was weathered from Archean rocks under anaerobic conditions and probably in the presence of sulphur-cycling, microbial communities. It was transported as a solution or a colloid, the gold being stabilized by humic acids of sulphur-cycle intermediates. Deposition took place in the presence of extensive, prokaryotic, microbial mats, now preserved as kerogen. Precipitation or flocculation occurred where oxygen was produced locally by the prokaryotic communities.

That the Witwatersrand strata have undergone metamorphism has long been recognized, but since 1986 more-definitive studies on this subject have been undertaken by Phillips and Myers (1987), Phillips et al. (1987), and Phillips (1988). Greenschist-facies metamorphism is pervasive. Temperatures reached 350-400°C, and the presently-exposed rocks were once at 3-10 km below surface. It has been put forward that the large volumes of fluids were produced, during prograde metamorphism, by the dehydration of the more-than-2000 metres of shales in the Lower Witwatersrand Division. Phillips (1988) considered the alteration-event to have taken place at between 2500 and 2000 Ma, well after the final sedimentation of the basin. A summary of the processes of mineralization involved is presented in Table 16.

TABLE 16

SELECTED NEW CONCEPTS OF ORIGIN OF WITWATERSRAND GOLD
CENTENARY MODELS I and II

syngenetic origin	:	Hallbauer (1982-1988); Robb (1986-1988) gold, uraninite, sulfides, 'carbon' granules, derived from hydrothermally-altered (propylitized, sericitized) granites in hinterland to NW
epigenetic origin	:	Phillips (1986-1988) gold, sulfur introduced into conglomerates by metamorphic aqueous fluids guided by faults, bedding-planes, unconformities, dykes; deposition of gold controlled by horizons rich in iron and kerogen; source of gold in metamorphic fluids not specified; ".... alternative genetic model to the placer (unmodified and modified) model is not offered ...."

Table 16 also contains an outline of a second, 'Centenary' model, reflecting the work of Hallbauer (1984, 1986), Hallbauer and Barton (1987), Klemd and Hallbauer (1987), Robb (1987), and Robb and Meyer (1985, 1987a), all of whom have carried out research into the granitic components of the region to the north, northwest, and west of the basin. Hallbauer (1986) concluded that the geochemistry of the quartz, pyrite, and gold in the Witwatersrand reefs was different to that of similar minerals from classic greenstone belts, such as the Barberton Mountain Land, but could be compared with that of some of the components of peraluminous granites which had been hydrothermally altered and which outcropped along the northwestern rim of the depository. Nodules of uraniferous, carbonaceous matter and small amounts of particulate gold were found to be present in the altered granitic rocks, as well as disseminated sulphides. The carbonaceous nodules were seen to be virtually identical to the 'flyspeck carbon' particles in the reefs. The fineness of the gold in the altered granite was found to be similar to that of the gold in the conglomerates, and the mercury contents were comparable. Robb and Meyer (1985, 1987a) considered the HAGS (hydrothermally-altered granites) to be related to the emplacement of large volumes of granitic magma at about 2800 Ma, at the same time as the Central Rand Group was being deposited. Because the introduction of potentially-fertile source-rocks, such as the HAGS, was coeval with this sedimentation, it was concluded that only the Upper Division was supplied by a source "able to provide the requisite budget of ore minerals".

A third model that was generated during the 'Centenary Dissection' suggested a source for the placer mineralization, which had not been considered previously. Hutchinson and Viljoen (1988) favoured an endogenous, rather than an usually-postulated exogenous, source for the gold. The novel concept of a syngenetic origin is outlined in Table 17. As in almost all other placerist

TABLE 17

SELECTED NEW CONCEPTS OF ORIGIN OF WITWATERSRAND GOLD

CENTENARY MODEL III

syngenetic origin : Hutchinson and Viljoen (1986-1988)

§ endogenous, rather than exogenous, source

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

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

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

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

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

theories, two separate sources were envisaged for the gold and the uranium. The former originated in the pyritic exhalites of the proximal facies of the Dominion and West Rand groups and was concentrated by mechanical reworking associated with fluvio-deltaic processes along a regressive basin-edge. Uraninite was derived from the erosion of the granitic terrane surrounding the basin and, therefore, was viewed as being exogenous. Magnetite and ilmenite in the erosional detritus passed through the zone of reducing, hydrothermal discharge along the margin of the depository and were sulphidized, to form authigenic pyrite and leucoxene. It was admitted that the amount of volcanism accompanying the deposition of the Witwatersrand strata was relatively small, but it was stressed that the andesitic-basaltic activity, which generated the hydrothermal discharge, was synchronous with, and geochemically similar to, the thick, Archean, greenstone successions which host significant lode-gold deposits throughout the world. A tectonically-less-active, more-stable, shallower, more-oxygenated, lower-temperature environment prevailed in the Witwatersrand depository than is typical of a rapidly-subsiding, Archean, greenstone belt. Cooler, oxygenated, biota-dominated conditions were more effective in breaking down the reduced, gold-complexing and -transporting agents and contrasted with the warmer, more-reduced, abiotic, coeval, greenstone-belt environment. The hydrothermal-discharge system along the basin-edge was a product of shallow-marine volcanism and was active at the same time as the formation of the HAGS. Hutchinson and Viljoen (1988) also drew attention to the fact that the new age of the Witwatersrand Sequence placed the contained mineralization in the same time-bracket as the majority of Archean lode-gold deposits.

Emanating from a re-interpretation of the geometry of the Witwatersrand Basin and its setting on the Kaapvaal Craton (Pretorius, 1986b), a fourth, new hypothesis has been suggested in Table 18. On the northwestern side of the depository lies an extensive tract of country paralleling the longitudinal axis of the basin. This tract contains an intriguing array of

TABLE 18

SELECTED NEW CONCEPTS OF ORIGIN OF WITWATERSRAND GOLD
CENTENARY MODEL IV

syngenetic origin : Pretorius (1986-1988)

§ Witwatersrand = back-arc basin; magmatic arc to NW

§ age of Witwatersrand Sequence = Late Archean (2700-3000 Ma)

§ pronounced activity in magmatic arc at 2800 Ma pene-contemporaneous with deposition of Central Rand Group

§ rapid succession of : porphyry-type and epithermal gold mineralization in magmatic arc → almost coeval erosion and fluvial removal → episodic deposition of detrital gold in distal braid-plains and braid-deltas of Central Rand Group (host to 98% of WWR gold)

§ reconstitution of reefs by pervasive metamorphic fluids emanating from continued activation of magmatic arc, including Ventersdorp volcanism (2400-2700 Ma) and Bushveld Complex (2000-2100 Ma)

§ Witwatersrand : simply, the jewel in the Golden Crown of the Late Archean

manifestations of igneous activity of different types and ages, including the Ventersdorp volcanics, the Bushveld Complex, the Palabora and Pilanesberg alkaline complexes, among several others, and many kimberlites, the most well-known of which is the Premier pipe. It is thought that this tract might have contained, within part of it, a magmatic arc, the presence of which is implied if the Witwatersrand is accepted as a foreland, back-arc basin. Possibly, the earliest tectono-magmatic activity in this arc might be recorded in the 2800-Ma-old granitic rocks and the associated HAGS. 'Centenary Model IV' places heavy emphasis on the pene-contemporaneous relation between tectonic activity, granite emplacement, associated hydrothermal and metasomatic effects, consequent highly-charged surface-waters, erosion, sedimentation of the Central Rand Group, and the introduction of mineralization. It postulates a rapid succession of emplacement of primary, high-level gold at 2800 Ma, of uplift of the provenance-region by thrusting and the diapiric rising of granite domes, of degradation and erosion of dominantly-siliceous material, of fluvial transport of erosional debris and detrital gold and uranium, and of deposition of these heavy minerals on unconformity-surfaces in 2800-Ma-old braid-deltas. There was repeated regeneration of source-material : no sooner was high-level porphyry- or epithermal-type gold mineralization emplaced than it was stripped away, only for another surge of primary deposition to bring further gold into the areas of uplift and erosion. The fluvial waters possibly contained some dissolved gold and uranium, and hydrothermal fluids, also hosting these metals, could have impregnated the coarser clastics while these were being laid down on the unconformities or shortly after deposition. Reconstitution of the gold, uranium, sulphides, and other matrix-material by pervasive, metamorphic fluids took place on at least four occasions between 2800 and 2000 Ma. This magmatic-back-arc version of the modified-placer theory is, in fact, a 'white flag' proposition hinting at the possibility that all three schools of thought in the Witwatersrand controversy might be right. Gold and uranium entered the conglomerates and other sediments as detrital particles, as dissolved constituents of fluvial waters, and as components of hydrothermal fluids at more-or-less the same time, in response to coeval tectonism, granitic magmatism, and fluvial sedimentation at the interface between a magmatic arc and a back-arc basin.

Current Thinking : a Summary

In the terminal years of the 1980's, it is apparent that a solution to the problem of the genesis of the Witwatersrand ores is being sought along quite different avenues to those travelled by the many, many contestants who fought the good fight in the first century after the discovery of the goldfields. 'Provenance', not 'Process', is now the banner on the battlefield. Sedimentation, metamorphism, mechanical reworking, chemical reconstitution, diagenetic-fluid percolation, hydrothermal-fluid permeation, all have been conceded to have left behind evidence of their involvement in the Witwatersrand saga. What is now being argued is the source of the gold, uranium, sulphides, and other heavy minerals in the reefs.

The long-held assumption that the gold had been derived from classic, Archean, greenstone belts and the uranium from the associated 'basement' granites has fallen from favour. Finer points of the mineralogy, including the nature of fluid-inclusions, isotopic compositions, the trace-element chemistry of individual minerals, fail to lend support to satisfactory comparisons with the Archean lode-gold deposits of the Kaapvaal Craton. It also has become increasingly apparent that, volumetrically, even the most-productive greenstone terrane known in the world would fall far short of requirements as a prospective supplier of the quantities of gold already recovered from the Rand reefs. No evidence has emerged which substantiates earlier contentions that the source of the hydrothermal fluids was in the Ventersdorp rocks, either as extrusive lavas or intrusive dykes.

One group of present-day researchers subscribes to the idea that the hydrothermal fluids were generated by dehydration, during greenschist-facies metamorphism, of the thick accumulation of argillites in the lower part of the stratigraphic succession. Although not positively stated, it might be taken as implied that the gold might have been present in the shales as a primary constituent. Other investigators also view the source of the gold as endogenous, but consider the source-rocks to have been pyritic exhalites resulting from the leaching of volcanics in the Dominion and West Rand groups. A third group claims the hydrothermally-altered, granitic rocks to the northwest and west of the basin to be the source of the gold and the uranium. The three lines of thought all agree that the uranium had an exogenous source. A fourth hypothesis envisages that sedimentation of detrital particles, precipitation from surface waters, and mineralization by hydrothermal fluids took place at virtually the same time in a highly-interactive environment where back-arc sedimentation and magmatic-arc magmatism and mineralization were intimately intertwined. The last-mentioned proposition sees the gold-bearing conglomerates as a consequence of a conglomeration of mineralizing processes.

The classification of the Witwatersrand Sequence as being of Early-Proterozoic age has had to be revised. The basin probably developed between 3100 and 2750 Ma ago, placing it firmly within the limits of the Late-Archean. It was being formed and filled at the same time as some of the Archean greenstone belts were evolving on the Rhodesia Craton and, possibly, on the Kaapvaal Craton. Consequently, it can be questioned whether the Witwatersrand can still be regarded as the product of an intracratonic basin on a stable craton. It might accord better with a foreland, back-arc environment. An older age also brings the Witwatersrand into the same epoch as encompasses the lode-gold mineralization characteristic of the Archean greenstone terranes of the world. In this context, it could serve to resolve the old enigma : with prolific lode-gold deposits' being a hallmark of the Late-Archean, why do significant paleo-alluvial fields appear not to have developed?

Future Approaches to Resolving the Controversy

What has been written so far is but an abbreviated summary of some of the observations and speculations that have been presented by a fraction only of the procession of geologists, which has marched its way, in time to many different drummers, along the Ridge of White Waters. What can be said, now, of future directions of research that might be pursued in attempting to resolve the riddles of this still-apparently-unique province of great ore-bodies? Five, ten years into the future, the avenues could well have turned towards other lands-of-promise, different to those outlined in Table 19, which, for the most part, reflects continuations of investigations that, in the closing years of the 1980's, already have been initiated. The flag of no new, revolutionary line of thought has been seen yet against the skyline.

TABLE 19

DIRECTIONS OF FUTURE RESEARCH INTO THE ORIGINS OF WITWATERSRAND MINERALIZATION

- Δ "It is surprising, then, that so little work is now being carried out on this 'hydrothermal action'. Surely it is imperative that the effects of 'hydrothermal action' be subtracted if placer action is to be understood". (Brian Skinner, 1986)
- Δ specific and detailed investigations of any possible structural control on variations in intensity of mineralization; is there a relation between reefs, cross-cutting faults, bedding-plane faults, dykes, and sills?
- Δ studies of the relations between the spatial distribution patterns of mineralogical, geochemical, fluid-inclusion, and isotope parameters of the mineralized conglomerates, the barren conglomerates, the quartzites, the shales, and the iron-formations of the Witwatersrand Sequence
- Δ investigations into the time and duration of hydrothermal alteration of the hinterland granites and into the similarities, or otherwise, of such alteration and the metamorphism of the Witwatersrand sediments
- Δ studies of the regional tectonic setting and the style of development of the Witwatersrand Basin and of the total spectrum of crustal evolution of the Kaapvaal Craton in which the basin is located

Some voices are heard, proclaiming that certain of the directions presented would be impossible to follow, because the cumulative effects of repeated, metamorphic overprinting and reconstitution would never permit the slate's being wiped clean, down to the very first chalk-lines of the story. Other protesters doubt whether most of the investigations suggested would yield any, more-definitive information than has been gathered already from research along lines allied to these themes. And, there are also those who label the five offerings as nothing more than a 'shotgun' approach, firing buckshot in all directions at once, in the hope that one pellet might make one, small indentation in the impenetrable armour in which Nature has dressed its treasure-house. It would seem that studies, in the near future, will have a bias towards further attempts to gain an understanding of the nature and history of the provenance-regions and of the tectonic setting of the depository within the Kaapvaal Craton. With so much time and effort already having been spent on the search for clues within the basin, it would not seem amiss to give added attention to what might lie on more-distant horizons.

In 1908, the President of the Chemical, Mining, and Metallurgical Society of South Africa concluded that the origin of the gold "is a subject which has been before us ever since these fields were discovered, and is likely to be before others when our mills have ceased to crush and our dumps are grass grown". Progress towards resolving the "continued difference of opinion" can be measured by comparing this prognosis with that submitted, almost 100 years later, by Skinner and Merewether (1986) : "We still fight over the origin of the deposit that was found a century ago on the farm Langlaagte, and it is likely we will be fighting long after the last grain of gold has been dug from the basin". Will we ever know what really happened on that golden shore so long, long ago?

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