ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
Johannesburg

THE DEPOSITIONAL ENVIRONMENT OF THE WITWATERSRAND GOLDFIELDS : A CHRONOLOGICAL REVIEW OF SPECULATIONS AND OBSERVATIONS

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SYNOPSIS

A review has been undertaken of the very large volume of information that has been published in the 89 years since gold was first discovered on the Witwatersrand. The literature has been surveyed for opinions voiced and theories propounded for the nature of the depository in which the sediments were laid down and the environmental conditions under which the gold- and uranium-bearing reefs were formed. The review has not been directed towards examining the arguments for and against the various hypotheses that have been advanced concerning the source of the metals and the mineralizing processes that emplaced them in the conglomerates, quartzites, and carbon seams. It is considered that about 90 contributions to the literature can be ranked as having added significantly to a better understanding of the depositional environment. It is apparent that, in the early period of mining operations, speculation favoured the conglomerates to have been formed on a beach. As limited amounts of quantitative data became available, preference was given to a deltaic and, later, a valley-flat environment. With the advent of detailed sedimentological studies, conclusions became far more objective, and systematic observation replaced subjective speculation. The result is that a fair degree of consensus now prevails on deposition having taken place along the interface between a fluvial system that brought the sediments and heavy minerals from an elevated source-area to the northwest and a lacustrine littoral system that reworked the material and redistributed the finer sediments along the shoreline. The goldfields were formed as fluvial fans that built up at several points along the northwestern periphery of the intermontane, intracratonic lake or shallow-water inland sea. Each fan was the result of sediment accumulation at the mouth of a river, which discharged through a canyon and flowed across a relatively narrow piedmont plain, before entering the basin. The review has also covered ideas on the origin of the carbon that is present in the sediments, since it has now been shown to be an important environmental indicator. Evidence is strongly in favour of the material representing the remains of algal colonies that flourished, at certain times only, about the mouths of the rivers. There is a suggestion that the plant-like forms might even have been more akin to lichens. Other ideas are subscribed to by many geologists, and there can be little doubt that, when the centenary of the Witwatersrand goldfields is celebrated in 1986, disputes will still be raging as to how and where the auriferous sediments formed.

INTRODUCTION

It is written in one of the accounts of the beginnings of the Witwatersrand goldfields that the Main Reef group of gold-bearing conglomerates was stumbled across on a Sunday morning, that there was general agreement by the Wednesday afternoon as to the discovery's being of unprecedented significance, and that by the Saturday evening a violent controversy was well under way as to what had been found. To this day, eighty-nine years later, no one single explanation of what the conglomerates really are has received universal acceptance. In 1887, only a year after the gold rush started, Mathers[1], wrote: 'Every second geological or more frequently non-geological expert who has visited the Rand has had a different theory to expound as to the origin of the banket. Where so much diversity of opinion exists among self-styled specialists the ordinary layman can take comfort

Professor D. A. Pretorius obtained his degrees at the University of the Witwatersrand where he studied mining geology. For thirteen years he worked for geological surveys, mining companies, private consultants, and foreign-aid programmes in various parts of southern, east, and north Africa, eastern Europe, and the Middle East. During this time, he was primarily concerned with geological, geophysical, and geochemical exploration for precious and base metals and groundwater. In 1959, he returned to the University of the Witwatersrand when the Economic Geology Research Unit was founded by the then Transvaal and Orange Free State Chamber of Mines. He is presently director of the Unit, as well as Professor of Exploration Geology. The main interests of Dr Pretorius include the nature of gold mineralization, the crustal structure of Southern Africa, and the distribution patterns in time and space of metallic mineralization.

to himself that his ignorance is not a distressing calamity and that it – sometimes – provides him with a little stock of that modesty which is always a welcome feature when found in mining circles'.

In July, 1886, four months after George Harrison and George Walker made their historic discovery on the farm Langlaagte, one alleged authority reported that the auriferous reefs would not continue to a depth greater than ten or fifteen feet below the surface. To him, the conglomerates represented the pebbly bed of a stream that had once run parallel to the ridge of hills. Owing to earth movements, the stream bed had been turned on edge, so that the depth to which the gravels would persist could not be greater than the original width of the stream. One year after digging started, Gardner Williams, the eminent mining engineer from Kimberley stated categorically, in March, 1887, that the conglomerates were merely surface deposits along ancient beach lines, and, because beaches were always narrow, no confidence could be attached to any predictions that the goldfields would have a long life.

Ballot[2], under the pseudonym Iones Beta, published in 1888 the first lengthy account of the mine workings that had developed around the Johannesburg camp. In his introductory preface, he stated:

> *Ever since the discovery of gold in the conglomerate of the Heidelberg, Potchefstroom and Pretoria districts, and more especially along the range of hills known as the Witwatersrand, there has been a considerable difference of opinion about the probable origin and the present position of this, as people supposed, entirely new and unequalled formation.*
>
> *Some predicted a speedy collapse, supposing the reefs to be mere alluvial deposits, certain to run out at no great depths from the surface. Others thought the reefs of volcanic origin, forced up from below and that the conglomerate would gradually turn into solid quartz with increase of depth.*
>
> *Another gentleman of practical reputation asserted the conglomerate to be of aqueous origin, formed under the ocean, but that it could not continue gold bearing, or go down to any depth; though not giving any reasons for such views, beyond saying that the reefs were bound to become barren or run out on striking the Silurian formation below.*
>
> *Again we heard it advanced that the conglomerate and sandstones were of aqueous origin, deposited at the bottom of an ocean or lake; but that the gold was a chemical deposit precipitated from the waters of the ocean; in which it existed in the form of chloride of gold held in solution.*
>
> *And lastly it has been held by some scientists that the conglomerates and sandstones are successive deposits of sand and gravel spread over the lake or ocean floors. That at certain intervals of time the floor of this ocean was ruptured by volcanic forces from below, and large quantities of auriferous lava in a molten state poured out and spread over these gravel beds, cementing them together. At the same time forcing the vapours of gold into and along the poured out gravel beds already covered up by beds of sandstone . . .*

The nature of the environment in which the conglomerates and other gold-bearing strata were deposited has obviously been a matter of considerable debate for a long period of time. Normally, three broad classifications of depositional environments are recognized: terrestrial or continental, marginal or transitional, and marine. Conditions in the terrestrial class range from fluvial, through lacustrine, paludal, and desert, to glacial; in the transitional category from deltaic, through lagoonal, to littoral; and in the marine grouping from neritic (low-tide to 200 metres depth), through bathyal (200 to 4500 metres), to abyssal (4500 to 7000 metres). All of these environments, with the exception of bathyal and abyssal conditions, have found their proponents among the substantial number of authors of publications on the Witwatersrand group of rocks and their contained gold and uranium mineralization.

The object of this paper is to present a critical review, in chronological order, of the observations that have been made by many of the authors and of the speculations offered by a much larger proportion of the writers on the subject. As is generally the case in the sphere of geology, fancies outweigh facts, by far. For this review, 350 books, papers, and articles were selected from an impressive volume of literature as possibly containing information relevant to the theme of the exercise. A total of 170 was found to include observations and ideas of worth. Only 90 publications, in the final analysis, could be considered as having made significant contributions to a better understanding of the nature of the depository and the conditions under which the sediments, both auriferous and barren, accumulated. The present work deals with these 90 books and papers. This figure leads to the conclusion that, on average, only one important publication has appeared each year since the discovery of the Main Reef in March, 1886.

The history of exploration and exploitation of the Witwatersrand mineralization appears to follow a 21-year cycle. The phases that have been recognized are as follows:

PHASE 1 (1886-1906):
- discovery of banket
- development of outcrop mines as small units to shallow depths
- Stage 1 of Central Rand goldfield
  - of West Rand goldfield
  - of East Rand goldfield
  - of Klerksdorp goldfield

PHASE 2 (1907-1927):
- amalgamation of small units for deep-level mining
- Stage 2 of Central Rand goldfield
  - of West Rand goldfield
  - of East Rand goldfield

PHASE 3 (1928-1948):
- discovery of extensive carbon seams
- South Africa goes off gold standard
- development of lower-grade mines
- introduction of geophysical prospecting in search for new goldfields

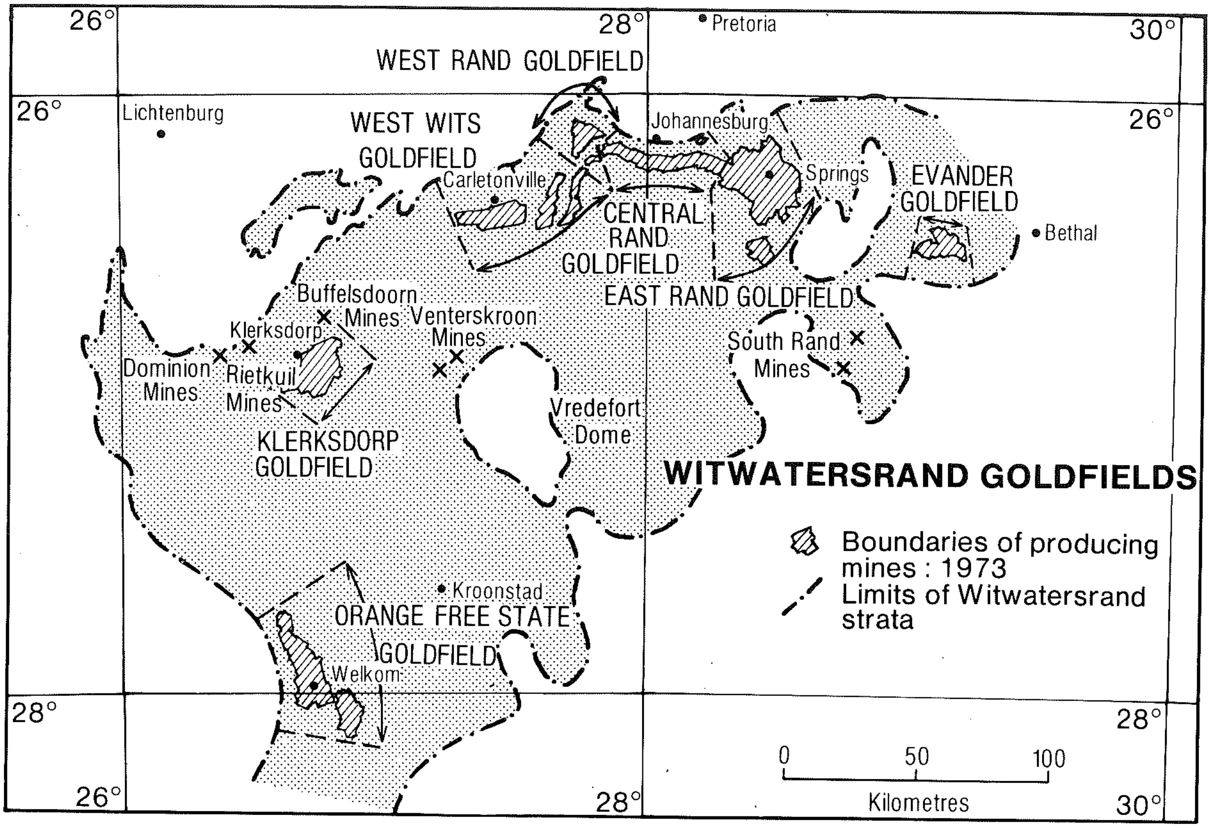


FIGURE 1 The location of the seven goldfields within the Witwatersrand Basin. The positions of the boundaries of producing mines at the end of 1973 are shown, as well as the presently known limits of Witwatersrand strata.

Stage 1 of West Wits goldfield
of Orange Free State goldfield
Stage 2 of Klerksdorp goldfield
Stage 3 of Central Rand goldfield
of West Rand goldfield
of East Rand goldfield

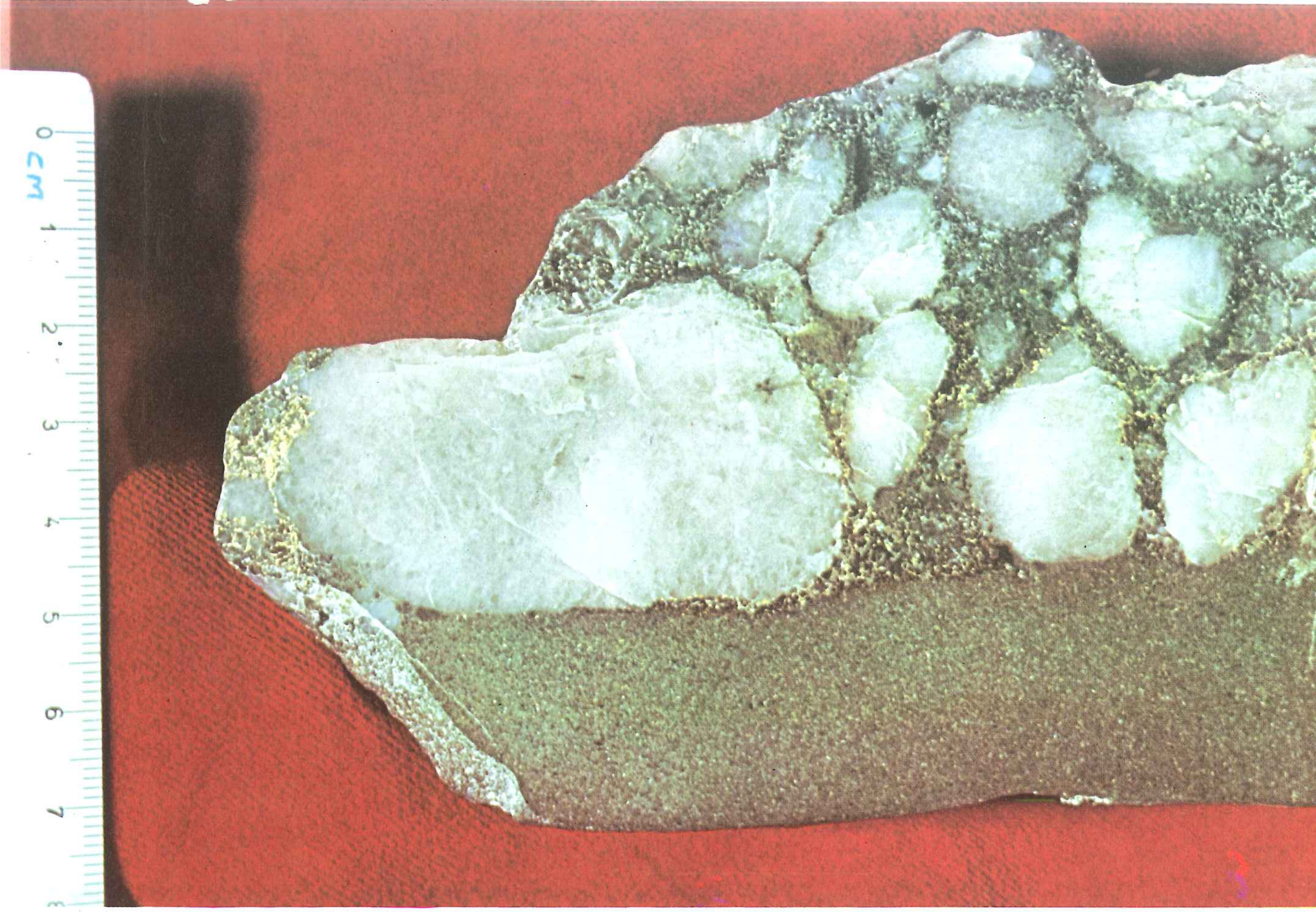
PHASE 4 (1949-1969):
recovery of uranium
devaluation of sterling and rise in price of gold
Stage 1 of Evander goldfield
Stage 2 of West Wits goldfield
of Orange Free State goldfield
Stage 3 of Klerksdorp goldfield
Terminal stage of Central Rand goldfield
of West Rand goldfield
of East Rand goldfield

PHASE 5 (1970-1990):
sale of gold on free market
Stage 1 of possible new goldfield(?)
Stage 2 of Evander goldfield
Stage 3 of West Wits goldfield
of Orange Free State goldfield
Terminal stage of Klerksdorp goldfield

The locations of the different goldfields mentioned above are shown in Figure 1, which also outlines the presently known limits of the Witwatersrand Basin.

The dates of publication of the more significant contributions on the depositional environment of the Witwatersrand strata have been grouped according to these five phases. In Phase 1, 12 papers merited serious consideration, in Phase 2, 19 contributions, in Phase 3, 12 publications, and in Phase 4, 42 books and papers. In the first five years of Phase 5, five publications are believed to have produced novel concepts of aspects of the mode of formation of the Witwatersrand conglomerate and carbon-seam auriferous horizons. The most fertile period for the generation of new ideas on the

FIGURE 2 (Top) Main Reef Leader from Crown Mines in the Central Rand goldfield. This is a specimen of conglomerate typical of that on which the Witwatersrand gold-mining industry was based for the first forty-odd years of its existence. The pebbles are exclusively of white vein-quartz, set in a matrix of quartz grains and flakes of phyllosilicates. The conglomerate rests with a sharp, planar contact on the Black Bar quartzitic argillite footwall. Detrital grains of gold are visible in the matrix and around the pebbles, a phenomenon which is rare in the banket. The specimen comes from depth in the vicinity of the discovery site at Langlaagte, southwest of Johannesburg, and portrays the type of banket that generally carries the richest concentrations of gold.
(Bottom) South Reef from the Robinson Deep Mine in the Central Rand goldfield. Two bands of conglomerate are separated by a narrow parting of coarse-grained pebbly quartzite. The pebbles are composed of vein quartz and several varieties of massive and banded chert, while the matrix consists of quartz, phyllosilicates, and abundant detrital pyrite. The foresets of cross-bedding within the upper conglomerate band are defined by oblique layers of pyrite granules. This type of banket is generally highly payable, but is not as rich as that exemplified by the specimen of Main Reef Leader.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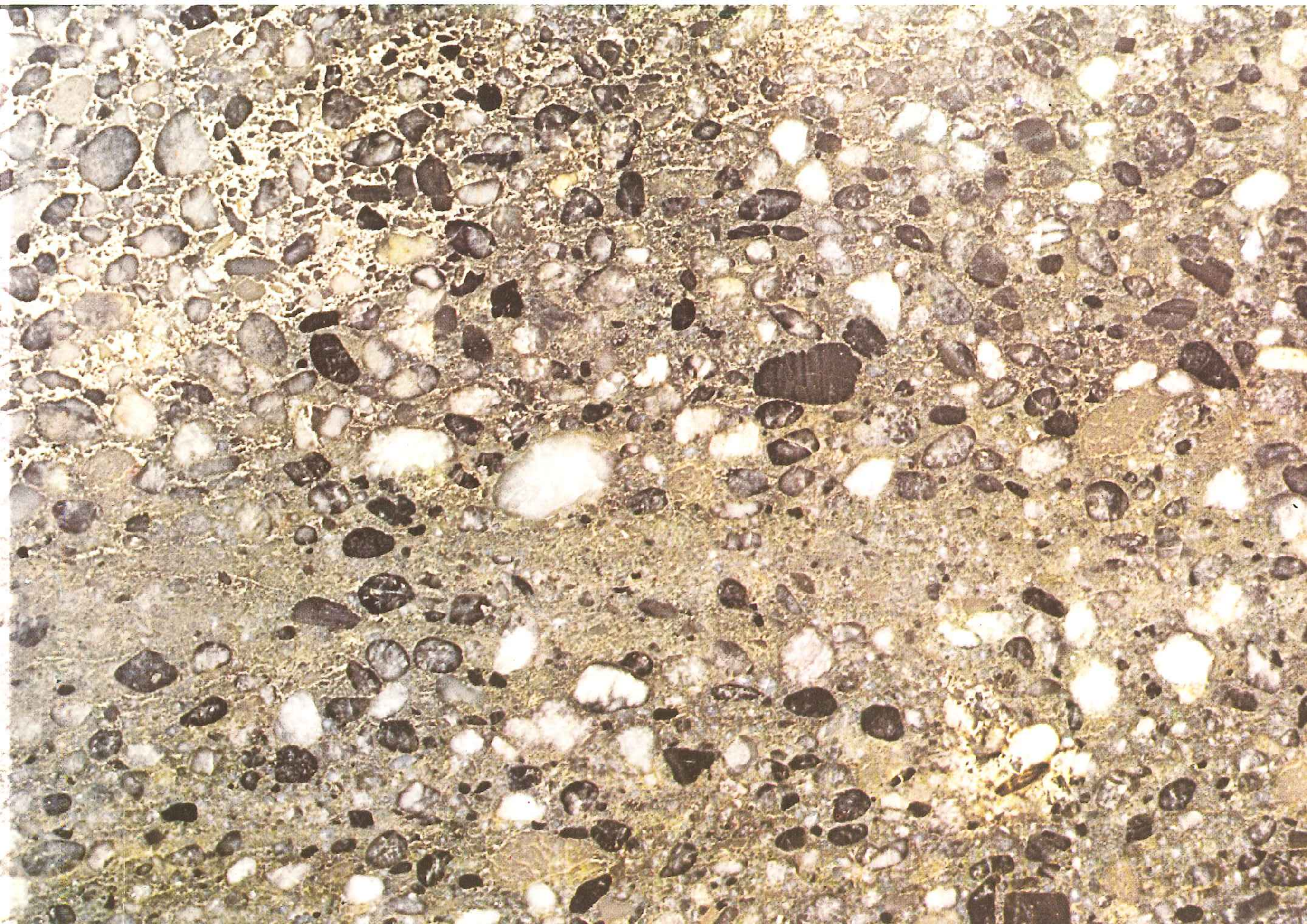

FIGURE 3   Columnar thucholite ('carbon') in the Main Reef Leader from East Geduld Mine in the East Rand goldfield. Abundant visible gold is apparent as thin filaments and platelets between the ovoidal columns of carbon. The material is now believed to have formed from a thin algal mat that grew on the surface of the sand layers which were deposited at the end of the footwall sedimentary cycle. Pebbles which washed in during the initial stages of the succeeding reef and hangingwall sedimentary cycle broke up the algal mat, leaving isolated remnants in situ, *as in this specimen, or mixing disintegrated material with the sand and clay of the matrix of the conglomerate. From the 1930's onwards, the carbon-type reef assumed progressively greater importance, especially as the result of the opening up of the West Wits, Klerksdorp, and Orange Free State goldfields. As a result, the proportion of gold and uranium won from the classic banket-type reefs has diminished over the past forty years. (scale in centimetres)*

problem was obviously the years between 1949 and 1969, when information became available in large volume for the important new goldfields beyond the limits of the original Witwatersrand. These good years saw geology, a rather poor relation of Witwatersrand mining practice in the three earlier phases, assume its rightful place in the hierarchy of research, development, and production in the greatest gold province the world has ever known.

In all the theories that have been advanced for the environment under which the accumulation and concentration of mineralization took place, five factors have had to be considered: (i) the nature of the conglomerates, both barren varieties and mineralized banket; (ii) the areal extent and distribution of the conglomerates; (iii) the variation in the composition of the sediments occurring above and below the mineralized horizons; (iv) the origin of the seams and granules of carbon, frequently extraordinarily rich in gold and uranium; and (v) the source of the gold, uranium, and other ore minerals in the banket and the carbon. The controversies, often acrimonious, which have been generated on the origin of the gold and uranium deserve a review to themselves, and will not be dealt with in this paper.

THE PERIOD 1886–1906

By 1888, the instantaneous impressions and immediate interpretations had run their courses, and serious thought was being given to the information that was rapidly accumulating from the mine development that was clearly showing that the Witwatersrand reefs were not the products of a shallow stream or of a narrow beach. In that year, Ballot[2] put forward the suggestion that older, auriferous quartz lodes had formed the rocky shores of a coast-line that was constantly undermined by waves and currents. The ocean advanced towards the land, destroying the coast-line as it transgressed, and on its floor the material from the shore was deposited. Periodic floods pouring off the adjoining highlands transported large quantities of gravel, grit, and mud over extensive areas of the ocean floor, adding to that gathered from the beaches. The farther the gravel was transported, the more waterworn and smaller the pebbles became, and the more gold was lost. He believed that the shales present in the Witwatersrand succession were laid down in deep, quiet water, well out into the ocean.

No further ideas of importance were presented until 1895 when publications by Hatch and Chalmers[3] and Kuntz[4] agreed with Ballot's conclusions that the conglomerates were marginal sea deposits. The latter regarded the shales as the products of an advancing coast-line and the conglomerates of a retreating shore. He thought that the coast-line was in a continual state of falling and rising caused by the folding of the crust. Kuntz was the first person to put forward the idea that the northern edge of the Witwatersrand basin occurred in the Johannesburg area and the southern margin in the northern Orange Free State.

In 1896, de Launay wrote that it was possible that the Witwatersrand strata could represent widespread fluviatile sediments deposited on torrential deltas distributed over an alluvial plain such as that which he had observed in Lombardy in Italy. However, his preference was for a marine beach origin because of the vast extent of the formations, the regularity of the beds, the frequent occurrence of shingle-type pebbles, and because the Witwatersrand conglomerates occupied an 'intermediate stratigraphic position between two formations known to contain marine fossils – the Bokkeveld beds and the Carboniferous limestones'. In the same year, Schmitz-Dumont voiced his disagreement with the generally prevailing ideas, and came out in favour of a fluviatile origin. The Main Reef he considered to represent the bed of an easterly-flowing river, which debouched onto a broad and large valley-plain. More than one river bed was formed in order to account for the great widths of the conglomerate horizons. The quartzites were thought to be the material formed on a delta or in an off-shore environment. As the continent subsided into the sea, the pebbles and sands that had formed in the river valleys gave way to river-borne sands and clays laid down in the sea.

The year 1897 saw the publication of an important contribution by Becker[7] of the United States Geological Survey, which became the most quoted study of the first phase of geological investigations. He could see no evidence for a lacustrine environment, because there were no large quantities of very fine-grained silt, because the coarseness of the conglomerates and sands showed the results of currents stronger than those that are developed in lakes, and because the areal extent of the gravels was too great to have been formed under lacustrine conditions. He viewed the presence of muffin-shaped pebbles, the absence of shingling, of regular imbrication of the pebbles, of river channels, of coarse nuggets, and of boulders, and the development of conformable stratification as convincing arguments for the depositional environment having been that of a marine beach. The currents flowed from east to west, in the same direction as the present currents around the southern African coast from the Indian Ocean to the Atlantic. The great thickness of the strata was considered to indicate substantial offshore subsidence. Becker saw similarities between the Rand deposits and the auriferous beaches of New Zealand and of the northwestern coast of the

United States. Denny[8], from his study of the Klerksdorp reefs, supported a beach environment where the action of waves was strongly felt. He added that '. . . the solidly pouring rains of Devonian times, when the heated earth was combining with the sun to evaporate ocean waters, from condensation in the upper rarified atmosphere, can easily be imagined of volume sufficient to create flowing seas of water, of which we can now have no possible illustration, and but faint conception'.

As the littoral origin became more and more the accepted theory, Carrick[9], in 1896, drew the attention of the various authors to the fact that Fred Struben, the original pioneer of the Witwatersrand area, at the very beginning of his mining of the conglomerates in the Lower Division of the Witwatersrand Sequence, considered the banket to be an ocean-beach deposit. At the same time, Garnier[10] put forward the first suggestion that the beaches had formed along a closed sea that was surrounded by high mountains, some of which formed a vast amphitheatre on the northern side. Streams converged in all directions towards the basin.

In the year 1898, Bleloch[11] described the Rand deposits as having some similarities to the Klondyke gravels. He saw the banket as a series of sub-shore deposits banked up by ocean currents and waves against a sloping shore. The alluvium was brought in by rivers and was spread over hundreds of miles on the offshore bottom. Bleloch introduced three important ideas. He was the first to question the generally held opinion that all the strata were completely conformable, and suggested that gradual subsidence at times produced estuarine deposits in a shallow tidal lake, and that, in such an environment, unconformity upon unconformity would have been produced. His was also the initial suggestion that, with recurrent subsidence and upheaval, the ocean currents caused previous deposits to be alternately overlapped and attacked, with later beds including some recycled material from earlier sediments. His third contribution was the suggestion that the original edge of the basin had not been that far removed from the positions of the present outcrops, so that little erosion had taken place of the Witwatersrand reefs. Prister[12], in 1898, also added his support to the shoreline concept. He thought that hot currents flowed along the coast, and that these were tidal, not ocean, currents. He visualized a large bay extending from the present Lebombo Mountains to Potchefstroom, with the water moving westwards because of the Earth's easterly rotation.

The last important contribution of Phase 1 was made by Hatch[13] in 1906. He subscribed to the theory that the material was derived from granites, gneisses, and schists of the Swaziland System, which were elevated to form a continental area. Rivers transported the debris to a shallow-water marine environment. The source-area lay to the west, and the sea to the east. The northern shore did not extend much farther north than the present site of Rustenburg. The clays and fine sands of the Lower Witwatersrand Division were laid down on a sinking bottom, whereas the conglomerates of the Upper Division accumulated on a rising bottom, with shallow water permitting the development of shingle and gravel.

In 1896, Schmitz-Dumont[6] wrote: 'Regarding the origin of the quartzitic sandstones, I have found some petrefacts in them like seaweeds'. However, it was Garnier[10], in 1896, who gave the first descriptions of the carbon, which had been observed associated with a number of the reefs in the East Rand, Central Rand, and Klerksdorp goldfields. He mentioned that the small carboniferous layer at the Buffelsdoorn Mine in the last-mentioned goldfield was a seam between one and five centimetres thick, which resembled lignite filled with gold. He suggested that 'organized beings' had flourished in the water, and that petrefaction of the decomposed organic matter had liberated gas, which precipitated gold present in the waters of the depository in the form of trichloride.

In summary, it can be said that Phase 1 of Witwatersrand mining history was a period in which speculation was rampant on the environment in which the gravels were laid down and the gold accumulated. Observations were almost exclusively qualitative, and no attempts were made to back up theories with quantitative data. The majority of investigators subscribed firmly to the idea that the conglomerates had been deposited along a marine beach and for a short distance off-shore. There were already suggestions that the source-area was a continental landmass to the north and west of the depository, that the sea was closed and surrounded by mountain ranges, and that later sediments contained contributions from reworked earlier material. The long-shore currents were generally believed to have flowed from east to west. Opinions were common that not much erosion of the Upper Witwatersrand Division had taken place, and that the original shore had not been too far removed from the present outcrops of conglomerate. There was one dissenting voice, which favoured a fluviatile origin for the gravels. Eastwards-flowing rivers deposited the pebbles on a large, broad valley-plain above a delta. Within the first ten years of mining, the importance of gold-bearing carbon had been appreciated, and it was thought that it had been derived from organisms that were present in the ocean waters.

THE PERIOD 1907–1927

Phase 2 opened with a notable contribution by

Gregory[14] in 1908, followed by a supporting statement in 1909[15]. This author saw the deposits as a long series of beach accumulations on a tide-swept shore where the material had been washed back and forth by the waves to yield a well-sorted end-product. The fines were removed to deeper water, leaving behind the pebbles to form small breakwaters, under the protection of which the fine-grained gold was concentrated. Channels were cut through the beach material by streams and tide races. Gregory concluded that ' . . . the rich auriferous sheets of banket represent intervals during the formation of the Rand Series when by a temporary cessation of deposition the gold concentration took place by tidal scour on the shingly shore'. He saw a resemblance between these reefs and the black-iron-sand-bearing beaches of New Zealand, where the coarse gold had been left upstream in rivers and only the fine particles had been carried to the beaches along which they had been distributed by currents. However, he admitted that the restriction of the gold to certain definite beds was not inconsistent with alluvial placer deposits. Gregory also put forward the thought that the Witwatersrand beds were of Precambrian age, and were not as young as so many of the early investigators had assumed.

In 1909, Becker[16] confirmed his original ideas on the development of the gold-bearing reefs, saying that they had been formed on sand beaches along rocky coasts. Violent storms had thrown up banks of pebbles far beyond the highwater line. A heavier surf had then moved the pebbles below the highwater mark, and the quieter waters of tides had transported the sand, which infiltrated and covered the pebbles. That year also saw a most important contribution by Young[17] who drew attention to the presence of payshoots of richer reef, which had not been recognized previously because there had been no syntheses of the data from the many mine workings. The most obvious payshoot he found to occur on the eastern part of the Central Rand. This zone of enrichment had a distinctly south-westerly orientation. Young believed that shallow-water conditions prevailed throughout Upper Witwatersrand times, and that the strata had accumulated in an area of subsidence with a slowly encroaching sea. Two years later, Young[18] reviewed the state of knowledge and opinion on the Witwatersrand deposits, and stated that it was generally agreed that the banket was a littoral marine deposit, and that during Main Reef times, at least, there were wide stretches of shingly beach. The conglomerates and ripple-marked quartzites were formed during periods of pronounced shallow-water conditions, whereas the conformable sediments, several miles thick, below the Main Reef Series had been deposited many miles from the beach.

The year 1911 saw the first publications[19,20] on the subject of this review by one of the most distinguished of all the geologists who have been involved in the problems of the Witwatersrand goldfields – E. T. Mellor of the Geological Survey of South Africa. Mellor's work marked the beginnings of systematic observation and measurement of the stratigraphy of the depository, and his work of more than sixty years ago is still the basis for much of the present-day classification of rock-units within the succession. He was the first person after Schmitz-Dumont[6] to doubt the generally accepted hypothesis that the gold-bearing reefs had been laid down on a marine beach. As a result of his extensive mapping, Mellor felt that the sediments were representatives of a very large delta in which there were interrupted, but progressive, cycles of changes from deep-water in the lowest portions of the stratigraphy, through deltaic phases, generating the conglomerates, in the middle portions, to actual shore conditions in the uppermost portions. He concluded that the reefs had not all formed in the same environment, and that some were the products of intermediate conditions and others of proximal conditions, with respect to distance from the shoreline. The papers by Mellor provoked long and bitter arguments, during which he remained very much the lone voice in the wilderness. Doubt was cast on the accuracy of his observations and the integrity of his conclusions, and he was accused of deliberately ignoring the work of other investigators. He had committed the almost unpardonable crime of introducing fact, instead of fancy, into his pronouncements.

By 1915, Mellor[21] had added a very considerable volume of additional observations to his information. He became even more convinced that the sudden changes from fine-grained sediments to conglomerates, such as occurred in the Government Reef, the Main Reef Leader, and the Kimberley Reefs of the East Rand, could only have been produced in an extensive delta. The most spectacular of these sudden changes he considered to be the Speckled Bed in the lowermost assemblage of Witwatersrand rocks. For the most part, the finer-grained material of the Lower Division was deposited beyond the limits of the delta, while the Jeppestown and Kimberley shales he believed to be the equivalents of modern delta silts. The continual increase in coarseness upwards indicated the gradual elevation of high ground to the north of the depository. As a result, the points of discharge of the sediments slowly approached the position of the Central Rand. By Kimberley-Elsburg times, towards the close of the sedimentary history of the basin, the shoreline had reached as far south as the vicinity of Johannesburg. Mellor believed that vast quantities of material had already accumulated along the lower courses of the rivers and the upper portions of the deltas, and were available for sweeping out by floods. Persistent beds, such as the Main Reef Leader, were laid down in a single period of sedimentation, the duration of the period being a matter of only days. The limited amount of information available from the then-developing East Rand led Mellor to two erroneous conclusions. He thought that there was an absence of cross-bedding in the payshoot conglomerates, showing that the Main Reef Leader had been laid down rapidly and continously over the whole area. He also believed that there was no erosion of the underlying muddy deposits of the East Rand, which would have taken place had there been a gradual extension of the pebbly deposits over them. Mellor compared the size of the area of development of the Main Reef Leader to the much greater extent of the deltas of the Ganges, Hoang-Ho, and Yang-tse-Kiang rivers.

Certain of Mellor's ideas were amplified in 1916[22] in another important paper. He drew attention to the fact that most of the previous studies had been concerned with the Main Reef of the West Rand and the Central Rand. The opening up of the Main Reef Leader of the East Rand had disclosed a new dimension that made many of the previous arguments untenable. He saw the Main Reef as representing widespread coastal plain gravels that had been modified by wave-action. The Main Reef Leader and South Reef had been laid down in a pregraded river or the upper part of a delta, and had not been affected by subsequent wave-action and coastal currents. The Bird and Kimberley reefs, he thought, were further examples of coastal plain gravels. With gradual elevation in the northwest and subsidence in the southeast, denudation of the Lower Division sediments probably took place in the later stages of the Upper Division. One of the main criticisms levelled against Mellor's theory was that it considered only the East Rand, Central Rand, and West Rand, and ignored such important sections of the Witwatersrand depository as the Klerksdorp goldfield. If the latter were included, it was argued that the total area embraced by Witwatersrand strata would have been too large to be accommodated within a single delta. His opponents contended that only an ocean could distribute material similar to the original constituents of the banket over such a great distance. Wagner[23] postulated that Mellor's suggested mechanism of considerable floods sweeping out material in rapid pulses would not have led to the development of conglomerates as extensive as those of the Witwatersrand. If the pebbles had been laid down in a large delta, then they must have been reworked by waves and currents during episodic subsidence of the littoral zone, in order to produce the shapes, sorting, and imbrication that characterized the banket. Wagner stated that the lenticular nature of the conglomerates and the splittings and partings of the reefs were also convincing indicators of the presence of beach gravels.

Discussion on Mellor's papers produced a highly significant new comparison by Evans[24]. He viewed the Witwatersrand depository as similar to that presently existing in northern India, adjacent to the Himalayas. A range of mountains to the north of the Central Rand would have filled the role of the Himalayas, which were previously much farther north than they are today. Faulted ground bounds the present mountains, and has been moving progressively southwards, so that the earlier alluvial deposits on the upthrown side have been raised above the plains from time to time, and have been eroded and swept down on to the plains by torrents from the slopes of the Himalayas. The gradual rise of the mountains and the subsidence of the plains has led to the frequent recycling of material derived from the uplifted highlands to the north. Evans pointed to the fact that many smaller streams are developed along the slopes of the Himalayas, rather than one large river. The argillaceous sediments in the Witwatersrand depository would have been brought to the plains by gentle streams, while the pebbles would have been the product of sheetfloods associated with great torrents. Towards the end of Witwatersrand times, when the mountain-front was at its closest to the basin, the force of the streamflow swept the gold farther out on to the plain, to give larger volumes of conglomerates with smaller amounts of gold. Evans felt that there was no vegetation at the time the Witwatersrand rocks were formed, that there was no organic matter in the depository, and that there was no oxygen in the atmosphere.

It was only in 1920 that the first sedimentological observations were made in the Witwatersrand goldfields. It seems difficult of explanation that, with the economic mineralization being so intimately associated with well-defined aspects of the sedimentary history of the basin, no attempts had been made at studying the sediments in their own right during the previous 30-odd years of exploitation of the conglomerates. Pirow[25], consequent upon a systematic investigation of the pebbles in the reefs, added his support to Mellor's deltaic theory for the Main Reef Leader of the East Rand. He found that the distributary action of the streams and their velocities and carrying capacities diminished to the southeast, and that, in the same direction, there was a corresponding increase in wave- and tidal action. Three distinct types of ripple-marks were measured, as well as interference ripples, in both the hangingwall and the footwall of the East Rand. The pattern of footwall erosion indicated clearly to him that water-courses had existed below the Main Reef Leader, and that potholes had been scoured out by eddies in these channels. Pirow concluded that the laying down of the gravels on a delta was succeeded by a short period of subaerial exposure and local denudation by rivulets and flowing waters. These streams also carried in the gold, and Pirow was thus the first to propose that the gold might have been introduced into the conglomerates by a later pulse of sedimentation than that which laid down the gravels.

In 1926, Rogers[26] published the results of his detailed mapping of the Heidelberg area at the southeastern extremity of the East Rand goldfield and the northern limit of the South Rand mining area. He took the absence of calcareous beds as firm evidence against deposition in a marine environment. The presence of fresh feldspars in the rocks indicated a cold climate, and the absence of pseudomorphs after salt pointed against an arid climate. The remarkably regular, but repeated, succession of coarse sands and fine sediments over great areas could have been the product only of sedimentation in a delta, so that Mellor's conclusions received further strong support.

The first edition of '*The Geology of South Africa*' by Alex du Toit[27] appeared in 1926. In this was synthesized all the major investigations of the Witwatersrand Basin to that date. Du Toit only partially accepted the correctness of Mellor's ideas on deposition in a delta. The strata that had been laid down off the mouth of a large river were periodically submerged by waves, as the ocean floor intermittently subsided, so that shallow-water sands and gravels alternated with deep-water muds. The depository stood close to sea-level, with the result that fluviatile and estuarine conditions intermingled. The gradual transgression of the shoreline produced the irregular shingling and the prevailing muffin-shape of the larger pebbles. Du Toit thus saw Mellor's delta as having been subjected to littoral reworking, with the result that the conglomerates, in their final form, could be more satisfactorily compared with modern marine placers.

Nel[28], upon the completion of his mapping of the Vredefort area, concluded that the Witwatersrand sediments around the dome had accumulated in the same basin and under the same conditions as in the Witwatersrand proper and the Heidelberg locality. The presence of widely distributed beds and the sudden passage from fine-grained shales to coarse-grained sands over extensive areas, he took as evidence of a deltaic environment, with the Vredefort area being farther away from the points of discharge than the goldfields on the northern rim of the basin. Through the work of Mellor, Rogers, and Nel, the Geological Survey of South Africa was a powerful advocate of the theory that the Witwatersrand conglomerates and other sediments had been laid down in a delta.

The second phase of mining history came to a close in 1927 with the publication of Reinecke's[29] sedimentological and other studies of the East Rand and the Central Rand. This paper and the contributions of Mellor rank as the most important publications on the depositional environment of the Witwatersrand gold deposits that were presented in the first 40 years of geological investigations. Reinecke was the first person to prepare contoured plans of assay values, and, of the result, he said: 'This brings out the variation in value in a striking manner and enables one to grasp the mass of detailed information involved with the minimum of effort'. These plans clearly delineated the numerous paystreaks in the Main Reef Leader of the East Rand, and showed that they had a fan-shaped arrangement, spreading farther apart southwards. A series of elongated, discontinuous lenses of conglomerate was shown to have radiated out from near Benoni, with the currents having moved eastwards and southeastwards, and their strengths having declined in the same directions. The current patterns assumed a braided configuration. Among his conclusions, Reinecke stated that: 'The deposition of the lenselike conglomerate bodies of the East Rand, in the shape of a fan or a wedge, can, moreover, not be reconciled with parallelism to a strand line. The plan of these currents and of the conglomerate lenses does, on the other hand, resemble that laid down by a river of continental proportion on its flood-plain in times of exceptional high water'. On the Central Rand, the paystreaks were shown to have a more braided pattern than on the East Rand, and were smaller, less consistent, and poorer in gold. They tended to spread apart towards the southwest, and the areal percentage payability diminished in the same direction. Two interfering trends of paystreaks – one oriented southeastwards and the other southwestwards – were recognized in the central part of the Central Rand. The Main Reef Leader on the Central Rand and the East Rand was seen to have been deposited as the products of either two separate floods or of contemporary distributaries from the same main channel, one having broken to the east and the other to the west, from a point north of Benoni. The Lower Witwatersrand succession of alternating shales and grits was viewed by Reinecke as showing depositional environments varying from a large body of water to the flood-plain of a river. Upwards, there were more and more beds with true terrestrial characteristics. The thinning of the whole succession from northwest to southeast indicated that the currents had moved in that direction. Reinecke found that he could not support Mellor's deltaic theory. He favoured the depositional environment to have been that of a river flood-plain at some distance from the sea. He introduced for the first time a glacial concept into the environmental regime. The most likely agent for carrying the exceptionally coarse material of the banket was considered to have been an ice sheet that picked up alluvial gravels in the foothills of a mountain range and deposited the load far down the broad plain of a continental river. The pebbles were laid down partly as outwash gravel in front of the glacier and partly as ground moraine. The rapid change from cold to warm temperatures, accompanied by the sudden melting of large volumes of ice, furnished the necessary flooding conditions. Strong evidence of a glacial climate was believed to be provided by the tillite band in the Lower Witwatersrand Division.

The presence of uranium-bearing material in the auriferous reefs was first reported during Phase 2. Pirow's[25] work with the pebbles of the conglomerates brought him in contact with the diamonds that had been recovered from the reefs on the northern side of the East Rand goldfield. He suspected that the frequent green coloration of the diamonds was the result of radioactive bombardment. Black-sand concentrates from five mines in the East Rand, two mines in the Central Rand, and one mine in the West Rand were submitted for analysis to Ettlinger of the Physics Department of the University College, Johannesburg, but he reported in 1920 that there were positively no indications of radioactive minerals in the material from the reefs. However, in 1924, Cooper[30] identified uraninite in concentrates gathered from mines between Boksburg and Roodepoort. He found that the Central Rand samples were richer in uranium than those from the East Rand, a conclusion that was not to be borne out by the detailed work on uranium carried out twenty years later. Reinecke[29] also stated that uraninite occurred only west of Boksburg. Because, at that time, uranium was not of economic importance, no further attention was given to its presence in the banket, with the result that its distribution and mode of occurrence made no contribution, during Phase 2, to a better understanding of the conditions under which the conglomerates were deposited.

The presence of carbon was further commented upon in the period between 1907 and 1927, but its significance in unravelling the depositional environment was not appreciated. The most interesting remarks during this 21-year time-span were made in 1908 by Spilsbury[31], an American mining engineer, who compared some features of the Witwatersrand with the placer gold deposits of California. He wrote:

> *. . . that the origin of the banket deposits appears to be that of a marine placer seems well proved . . . I am, however, of the opinion that he [Gregory[14]] pays too little importance to the rôle that organic matter has played in the collection, or concentration, as well as in the deposition of gold in the gravel of the coastal rim . . . I am more and more impressed with the fact that the distribution of fine gold in the sedimentary deposits, as well as in some of our placers, is due mainly to organic agency . . . I think one of the best examples of the extent of this agency is in the recent growth of a new industry on some of our western rivers known as 'Moss Mining'. On the Trinity River in California, a stream which runs through some of the best gold-bearing ground in the State, and has rich placer ground on both banks nearly over its whole length, there occurs during the summer season of low water a heavy growth of algae in the low pools along the banks, and a species of dense moss covers the banks. These plants are constantly being submerged during local floods, and again on the water retiring subjected to the burning heat of the sun, so that partial decomposition is always going on. During the rainy season these growths are entirely covered by high water . . . Now it has been discovered that these plants contain considerable gold, and every spring, towards the end of the rainy season, the miners build light flat boats and float down on the last day of the flood, collecting these mosses and water plants, stocking them up and washing them for their gold contents . . . the function of the plant life in these cases is probably to a great extent mechanical, as the fine gold caught on their surfaces, while flaky and excessively fine, does not show sharp edges, and is generally dull on the surface; but in examining samples under the microscope we find quite a number of bright hair-shaped particles bent at different angles and having all the appearance of embryonic crystallization. This would tend to prove that the river waters carry gold in actual solution as well as in suspension, and that this gold is precipitated, probably on that part of the plants which is undergoing decomposition. Now, it seems to me that if this faculty of organic matter, or plant life, as a collector as well as depositor of gold is so active at the present time, and in fresh water, it is reasonable to assume that it was no less active on the shores of that great Devonian sea, during which epoch the algae grew in such remarkable exuberance. If instead of an exposed wave-lapped beach we should assume a coastal lagune, separated from the ocean by a sand bar, which from time to time might be broken over and inundated during violent storms, should we not have before us the ideal conditions for the distribution of gold in the banket under the exact conditions described by Professor Gregory . . .*

In 1909, Young[17] reported that carbon had been observed in reefs of seven gold mines in the Central Rand, East Rand, and Klerksdorp goldfields. In the following year, Horwood[32] presented the first systematic description of the carbon, and stated that it was present in most reefs, but was only well developed in the few mines which Young had mentioned. Horwood recognized that the presence of carbon indicated good values, even where no pebbles were present, and concluded that: 'There can hardly be any reasonable doubt that there is some clear, subtle connection between the presence of carbon and that of gold'. He did not think that the carbon was of organic origin, but saw it as being associated with an eruptive magma. There was a solfataric volcanic origin for a natural series of carbon compounds constituting petroleum, graphite and diamond being the end-products of this petroleum series. The carbon in the banket was thought to have been introduced by the longitudinal diabase dykes of Ventersdorp age that are abundantly present in the Witwatersrand strata. Young[18] considered the carbon to be essentially the same as anthracite, but doubted whether there was any abundance of organic matter in the original sediments, although he quoted other workers as saying that the '. . . beach was not the most salubrious, and the air was already tainted with mephitic exhalations from decaying seaweeds . . .'

The second phase in the development of the Witwatersrand goldfields can be seen, in summary, to have been a period in which a number of significant changes were made in the ideas held about the nature of the depository in which the auriferous conglomerates accumulated. In addition, several new lines of investigation were initiated and concepts developed. Quantitative sedimentology was employed for the first time, in two separate investigations, but was not adopted as a standard technique, despite the fact that it yielded exceptionally useful new data. Contoured assay plans were developed, which revealed, in considerable detail, the distribution patterns of gold in the reefs and the limits of payshoots. It was put forward that all the reefs had not formed under the same conditions, and that different environments had led to the generation of different types of conglomerates with varying percentages of payability. The overall history of shrinking of the depository was emphasized more than once, and the importance was realized of the edge of the basin advancing closer and closer to the centre with time. The presence of uraninite was recognized, but it was not then of economic importance, and it contributed nothing towards a better appreciation of the depositional environment. The close relationship between high gold values and carbon emerged in several investigations. A suggestion that its origin might have been similar to that of the gold-extracting fresh-water algae of streams in the California placer goldfields was not deemed worthy of further consideration. In the early years of Phase 2, the majority opinion still saw the banket as a marine littoral accumulation. With the passage of time, this theory was seriously challenged, first, by the proposal that the conglomerates had accumulated in a large delta, and, second, by the argument that the banket was deposited in braided, fan-shaped channels on a fluvial floodplain at some distance from the sea. Differences of opinion existed as to whether the fluvial and deltaic material had been reworked later by littoral waves and currents. Up to virtually the end of Phase 2, all authors had agreed that rivers and streams had carried the pebbles and other sediments from a highland source-area to the river valley, or the delta, or the beach, or the off-shore ocean floor. Then, an entirely new theory was offered to the effect that the vast quantities of pebbles and boulders had been brought into the depository by glaciers. A great deal more observation was beginning to challenge the ideas built on the speculations of the first phase.

THE PERIOD 1928 – 1948

Phase 3 was hallmarked by the great controversy that arose about the placer *versus* hydrothermal theory for the mineralization of the banket. This was sparked off in 1930 by the publication of Graton[33], one of the foremost economic geologists in the world at that time, who lent all his authority to the hydrothermal school. The protests from South African geologists were long and voluble. Among the arguments that surged back and forth, there were several opinions voiced on the nature of the depository itself. Graton remarked that the conglomerates had a notable constancy of thickness and a remarkable areal continuity. The sediments were well sized and the sands clear and well sorted. The pebbles had a small size-range, were closely packed, well-rounded, ellipsoidal, and without marked imbrication. No cut-and-fill features were visible and lenticular bedding was strikingly absent. Some of these statements were wide of the truth, thus adding further to the indignation of the local geologists. He threw more fuel on the fire by claiming that: 'The accumulating confirmation of the essential conformity of the system from top to bottom, notwithstanding intensive search for unconformities, indicates a notable degree of uniformity and constancy in the dominant conditions and controls of sedimentation throughout the duration of this accumulation and over the whole of the area as now known'. All the above features, Graton believed, pointed firmly against the conglomerates being river-valley, deltaic, or beach deposits. Instead, he favoured neritic marine deposition on a nearly flat, even continental shelf, which underwent a gradual decrease in depth of water with the passing of time. Milling on a beach had produced the pebbles that were alternately carried away to deeper water by the undertow and returned to the beach for further milling. As soon as the beach mill had reduced the pebbles to the requisite degree of size and roundness, they were transported out to an off-shore position for the last time and there deposited. The pebbles were laid down without interstitial sand, which was washed in later. Contrary to almost all previous authors, he concluded that the East Rand had a shoreline that ran northwestwards, instead of northeastwards. He envisaged the greater part of the East Rand as having formed under deeper water, the Central Rand under shallow water, and the West Rand under deeper water, with the highlands being to the northeast and east-northeast of the East Rand, again the opposite to all the observations that had shown that the basin fill had moved from the northwest.

In 1930, Reinecke[34] expanded on his earlier contribution. Crossbedding was measured for the first time, and was found to be inclined in the direction of the paystreaks. He modified to a slight extent his earlier conclusions, stating that the Witwatersrand beds were laid down partly on a flood-plain of a river and partly over a piedmont area on the foothill slopes of a mountain range. A series of uplifts to the northwest caused the mountainland to approach gradually nearer the Witwatersrand proper. As it moved southeastwards, proximal facies were stacked upon distal facies. The earlier sediments in the northwest were progressively uplifted on to the mountain flanks from where they were removed by erosion and were fed back into the depository. The uniform, thin conglomerates were laid down between the piedmont and the lower flood-plain. Sudden increases in river volumes picked up the alluvial fans on the piedmont, and swept their contents over the plains below, with the result that the reworked sediments covered a much wider area than the alluvial fans, and were transported over flood-plain deposits, over channel deposits, over lagoons, and over the mudflats of the lower plains. The Main-Bird sediments were formed near to the mountain area, with the delta-plain much farther southeast towards the sea. Reinecke doubted whether the gravel sheet had ever extended as far as the seashore. In his attempts to find an analogue of the Witwatersrand environment, Reinecke revived Evans's[24] suggestion that the region straddling the southern foot of the Himalayas and the upper valley of the Indus River, in the northern portion of India, might hold the key to understanding the manner in which the banket was laid down. The Miocene-Pliocene Siwalik System of fluviatile origin was thought to bear strong similarities to the Witwatersrand succession.

Du Toit[35] disagreed with Reinecke's interpretations, maintaining his argument that only marine conditions could have given rise to such extensive pebble deposits. A shoreline advanced northwards, and immediately south of it sand and pebbles spread out at just below tide-level. He believed the Main group of conglomerates to be the outcome of the waning and cessation of such marine planation, of the establishment and consequent destruction of estuarine conditions, of the reworking of vast sheets of marine gravel by braided streams, and of the swamping of these deposits by sands and pebbles brought down from a rapidly rising interior with its mountain ranges advancing towards the depository. The Kimberley Shales, he thought, represented good examples of the establishment of estuarine or lacustrine conditions. In 1931, also, Gregory[36] restated his conclusions of more than 20 years earlier. The banket had been deposited on the southern slope of a mountainous coast-line where tidal action and backwash had produced the inconsistent pebble imbrication. The Main Reef Leader and the South Reef of the Central Rand could be viewed in no other light, but Gregory was prepared to concede that the Elsburg Reefs, formed in the closing stages of the Witwatersrand Sequence, could have been fluviatile, or perhaps deltaic, accumulations.

In criticizing Graton, Mellor[37] also re-affirmed his thoughts on the Main Reef Leader of the East Rand as having been formed on a deltaic fan. He stated that developments in the East Rand had served to produce only further evidence in support of the conclusions that he had drawn 15 years earlier. His comments on Reinecke's views emphasized that the main question that had to be settled was whether the conglomerates were the result of the actions of a number of rivers discharging from a mountainland on to an adjacent alluvial plain, or of some larger unit depositing material much farther from its source. On the completion of his mapping of the Klerksdorp area, Nel[39], in 1933, found his observations inclining towards either Mellor's delta theory or Reinecke's fluvial hypothesis. His earlier work in the Vredefort area had led him to believe that only the delta concept had merit. The Geological Survey[40] published, in 1936, its handbook on the mineral resources of South Africa, and gave its support to both Mellor's and Reinecke's ideas. It also quoted a verbal communication from Professor Douglas Johnson of Columbia University, who had ventured the opinion that the Main Reef Leader was similar to a gigantic piedmont alluvial fan deposit laid down on a nearly flat plain in front of a mountain range. He had observed such fan deposits to be made up of conglomerate lenses with a braided fan-shaped pattern. The texture and arrangement of bars in the Main Reef Leader did not appear to resemble marine or flood-plain deposits, while the variations in texture between the centre of the payshoots and the inter-payshoot areas were the same as those that could be seen on an alluvial fan.

In 1938, Roberts and Kransdorff[41] provided the first substantial evidence to show that the major conglomerate zones were in contact with distinct disconformities. The significance of this conclusion was to assume ever greater importance as more and more detailed studies were undertaken of the Witwatersrand reefs. Their work in the West Rand led them to concur with Du Toit's[27] ideas on the existence of shallow marine conditions in the Main Reef series of conglomerates. Oscillation ripples in intercalated shales were interpreted as marine current ripples produced by water moving from west to east. The lenticular nature and wide variations in character of the Bird Reefs were ascribed to their having formed under continental conditions. The presence of dolomitic shales and of an oolitic bed in the Kimberley Shales pointed to deep-water marine conditions, while a continental environment again prevailed during the formation of the Kimberley Reefs.

In the second edition of his textbook, published in 1939, Du Toit[42] said that the recognition of one tillite horizon in the West Rand and two at Klerksdorp indicated that glacial and fluvio-glacial conditions might have been more widespread than previously thought. The presence of wind-faceted dreikanters in the Promise Reef of the Lower Witwatersrand Division was also mentioned. Du Toit felt that there was no necessity to change the views he had held in earlier years. The worn-down southern part of the Transvaal had been invaded from the south by a shallow sea in which were deposited sands and muds during the middle period of Witwatersrand history. The emergence of the sea-floor produced extensive beaches, and ultimately led to the development of great delta-flats on which river systems from the northwest discharged sands and pebbles. Auriferous black sands were associated with the gravels. There was an abundance of gravel supply from accumulations partly of glacial origin in the interior mountains. Ultimate elevation in the north and northwest uplifted and denuded the Lower Division sediments, to give abundant coarse material for the Elsburg conglomerates. The planes of unconformity, the irregular shingling of the banket, and the muffin shapes of the larger pebbles were all still considered to be indicators of the gradual transgression of the shoreline.

The discovery of the new West Wits goldfield, which was to change many of the concepts previously held about the conditions under which the Witwatersrand reefs formed, led to De Kock's[43] paper in 1940 on a new reef of major economic importance – the Ventersdorp Contact Reef, present at the very top of the sedimentary assemblage. De Kock interpreted this horizon as being constituted by eluvial scree that had accumulated on an old land surface, with thicker sheets in the depressions, valleys, and stream beds. The nature of the reef, its mode of occurrence, and the gold content were described as varying with the morphology of the pre-Ventersdorp landscape. The detritus had not been subjected to prolonged or continuous wave-action. Thicker reef bodies were thought to be due to seasonal accruals of layers upon layers. The Ventersdorp Contact Reef was seen by De Kock as being a partly eluvial and partly alluvial placer deposit, and as representing the erosion product of the immediately underlying Witwatersrand formations, from which were derived the pebbles, the quartz particles, and the gold.

Nothing of any significance was written about uranium during this period, and its presence in the gold-bearing strata was all but forgotten. A minimum of new information was provided on the carbon deposits, despite the discovery of the exceptionally rich Carbon Leader of the West Wits goldfield. In 1931, Macadam[44] reported that very little visible gold was ever found without carbon being present. This substance was plentiful, not only in the banket, but also in bedded pyritic seams where no pebbles were present. Mellor[37] stated that, in the N.A. Leaders of the East Rand and the South Reef of the West Rand, very rich gold-bearing carbon was often present as a thin 'pencil line' on an obscure bedding plane. The only comment made during this period on the possible origin of the carbon was that by Du Toit[42], in 1939, to the effect that liquid and gaseous hydrocarbons had formed from organic matter.

To summarize the contributions made during Phase 3 to the arguments concerning the manner in which the auriferous horizons in the Witwatersrand Sequence developed, it is probably correct to say that, except for the first three years, it was a relatively non-productive period. It was a time of quiescence before the flood of papers that were to be presented during Phase 4. No new approaches were adopted towards settling the differences of opinion. Nothing was written about the uranium or the carbon in regard to their possible use as indicators of the depositional environment. Three main schools of thought prevailed – those supporting the previously postulated littoral, deltaic, and fluvial theories. However, there were signs of more observers beginning to subscribe to the idea that all of these had prevailed at one time or another, and that different reefs had not necessarily been formed in the same environment. There were reefs and reefs. At the beginning of the period, a new hypothesis was put forward to the effect that the gravels had been laid down in a neritic environment where the water was of substantial but not excessive depth. In the closing stages of Phase 4, the opening up of the West Wits goldfield encouraged a further theory that the terminal reef of the Witwatersrand Sequence was an eluvial and alluvial accumulation.

THE PERIOD 1949–1969

Time might well show that the fourth phase in the history of Rand mining was the golden period of Witwatersrand geology. In the twenty-one years between 1949 and 1969, as many significant contributions were made to an understanding of the depositional environment of the auriferous strata as were published in the previous 63 years. The primary reason for this was the opening up of the extensions of the Witwatersrand basin and the addition of voluminous new data from the Orange

Free State, Klerksdorp, West Wits, and Evander goldfields to supplement that which has formed the basis of the arguments concerning the origin of the reefs in the West Rand, Central Rand, and East Rand goldfields. The numbers of geologists employed in the gold mining industry increased exponentially. The complexity of the problems brought to light in the new fields demanded that quantitative studies be carried out, so that information became more accurate and less subjective. The uranium industry came into being, requiring that the uraninite component of the reefs be studied in immeasurably greater detail than before. The newly discovered reefs did not conform to the conclusions that had been drawn in regard to the classic conglomerate horizons, and it became ever more apparent that the origin of the carbon would have to be understood before the depositional environment of such new reefs as the Basal Reef of the Orange Free State goldfield and the Vaal Reef of the Klerksdorp goldfield could be determined. In 1959, the Economic Geology Research Unit was founded for the express purpose of working on the geological problems of the gold mining industry, and one of its first projects was the re-introduction of sedimentological methods into the gathering of data. The Geological Society of South Africa brought out, in 1964, a two-volume collection of papers on the geology of some ore deposits in Southern Africa, one volume being devoted in its entirety to the Witwatersrand basin. Throughout the whole period, geologists were encouraged to return from industry to universities for higher degrees, with the result that an appreciable amount of research was carried out on aspects of the stratigraphy, structure, sedimentology, and mineralization.

Sharpe[45] produced a valuable contribution in 1949, in which he stressed the cyclic nature of the sedimentation throughout the whole of the Witwatersrand succession. He recognized primary oscillations on a regional scale and secondary ones on a local scale, and attributed these to regional movements of uplift and subsidence, which progressively decreased in intensity stratigraphically upwards, so that, by the end of Witwatersrand times, conditions had become almost static. He viewed the argillaceous sediments and erosion channels filled with coarse debris in the footwall of the Main Reef Leader of the East Rand as typical lagoonal deposits. The Main Reef, Main Reef Leader, and Kimberley reefs were considered to be shoreline pebble deposits that settled on a wave-cut plane of erosion when the surrounding land was of low relief. The concentration of the gold took place during a gradual but relentless advance of an encroaching sea-front. He also emphasized the point that the payable reefs represented the initial deposits formed after a considerable break in sedimentation.

The idea of a neritic environment, put forward by Graton[33], was revived by De Jager[46,47,48] in a series of publications dating from 1949 onwards. His interpretations dealt specifically with the May Reef of the Kimberley group of conglomerates, which he saw as both depositional and lag gravels formed by wave-induced erosion of the underlying sediments. The associated chloritoid shales he thought were typical neritic accumulations on a shelf bordering an open sea. De Jager also subscribed to the idea that ice had played a major role in transporting material from a source-area to the marine shelf. The Elsburg Reefs, in particular, were seen as the representatives of ice-rafted coarse material, which had been dropped in the sea on to finger-grained material in the neritic environment.

The first detailed account of the Orange Free State goldfield was presented by Borchers[49] in 1950. He believed that the terrain in which the Witwatersrand depository formed contained distant, high, cold mountains above arid wastes of Archean basement rocks and disintegration products. Crustal movement associated with the outpouring of the Dominion Reef lavas had trapped a body of water. A flood-plain developed either in an inland valley-flat or on the landward side of a delta. Climatic fluctuations and extremes of temperature led to rapid and drastic break-down of the rocks. Cataclysmic floods transported vast quantities of detritus into enclosed basins where the rates of evaporation were very high. On occasions, glaciers reached the basins to deposit fluvio-glacial grits and tillite. Wave-action eroded the edges of the uplifted unconsolidated sediments, and a shoreline was formed, on which the coarser and heavier materials were concentrated. Because the basin was a shrinking depository, there was a progressive advance of the shoreline into the basin, the distance of the total advance being of the order of 50 km from the top to the bottom of the Witwatersrand Sequence. The numerous marginal unconformities which were apparent in the Orange Free State goldfield suggested that the present outcrops of the Upper Division lay close to the original limits of deposition. In fact, the Elsburg Reefs might well have been formed right on the edge of the basin, since they were constituted by detrital cones below faulted elevated ground, the fault being one of the bounding structures of the original basin.

From his studies of the Livingstone Reef in the West Rand goldfield, Pegg[50] came to the conclusion in 1950 that the conglomerates had resulted from a river discharging course pebble debris into an estuary. The gravels were washed in during flood periods. While the floor of the estuary was deep, little or no sorting took place; when it was raised by the accumulation of sediments, sorting occurred through the medium of wave-action, the pebbles remaining in the estuary and the argillaceous material being washed out to sea.

A notable synthesis of the geology of the basin was presented by Antrobus[51,52] in 1954 and 1956. The depository was seen as a continental feature, surrounded by land on all sides, the margins being close to the limits of the present extent of the Witwatersrand strata. Faulting, warping, and erosion were conspicuous on the periphery. The optimum conditions for reef formation were set during periods of stillstand and reduced sedimentation, accompanied by some erosion of the footwall. The economic reefs were located on disconformities, and represented the basal beds of a group of overlapping strata. Antrobus concluded that the reefs had been formed from detritus left on a pediment after a long period of subaerial weathering and concentration. These were exposed pediments and not bajadas of coalescing alluvial fans. The reefs accumulated on an erosion surface along the margin of the basin, the surface having been either completely dry or occasionally covered by thin sheets of water as a result of streams from the hinterland debouching on to it. The economic horizons represented material left upon the surface as a product of the disintegrational effects of attrition and weathering and of the washing effects of flood-waters. The debris took the form of a loose, unconsolidated, thin layer of sediment derived from the underlying rocks and from occasional inwashings. The less durable components were removed by sheetwash, floods, and winds. The paystreaks he considered to be braided streams produced during occasional floods when the material on the exposed surface was picked up, transported, and redeposited along the lines of strongest flow of flood-waters. In the Orange Free State and Klerksdorp goldfields, especially, there were many marginal faults that formed escarpments. Repeated uplift along the periphery caused the upthrown sides to be eroded and the debris to be deposited with the younger members of the succession. Antrobus provided the first detailed description of the facies changes along a particular horizon. Near the basin-edge, the reef was thicker, the pebbles more variegated, the conglomerates more lenticular, channels present, and the gold content low. Farther in, where washing and weathering were most effective, large pebbles were few, the reef thin, and the richest concentration of gold present. Towards the centre of the basin, the area was more often covered by water, with the result that the pebbles were smaller, the percentage of fine material greater, and the quantities of gold and other heavy minerals less. During the formation of the Witwatersrand rocks, there was no vegetation and little rainfall, and the climate was cold, as indicated by the presence of tillites and the absence of red coloration and saline deposits. Antrobus saw an analogy to the Witwatersrand environment in the Basin and Range Province of the western United States, where pediments form during periods of stillstand and are then eroded laterally by ephemeral and braided desert streams.

Brock[53] also presented a broad overview of the Witwatersrand Basin in 1954. He was convinced that it was a continental feature, with no encroaching ocean, ringed by granite mountains. These were lowered by erosion, and then re-elevated by vertical uplift, thereby maintaining the rim of the basin for a long period. There was no vegetation and no signs of life, the conditions were desert-like, and the climate was marked by heavy rainfall. Torrents swept gravel into the basin from all sides. Subsidence was gradual and sedimentation kept pace, so that shallow-water conditions, at least in the Upper Division, prevailed. Differential movement on the peripheral faults led to the development of several fan-like bodies of conglomerate at three points around the basin, at least – north of the Central Rand, west of the Klerksdorp, and west of the Orange Free State goldfields.

In the third edition of his textbook, which appeared in 1954, Du Toit[54] reiterated his continuing belief in the marine placer origin of the banket, the reefs being drowned pebble beaches that had extended progressively landward during regional subsidence. Reef formation was always intimately connected with crustal adjustments. An invading sea from the southeast caused marine planation, and pebble bars, graded by shore currents and pulsated by waves, advanced northeastwards over a subsiding coastal plain composed of loose deltaic materials and blown sands. In the same year, Miholic[55] wrote that deltas had formed in fairly deep water along a steep coast, and that the reefs had developed from the marine gravels accumulated in such an environment. He envisaged that the conditions must have been similar to those prevailing in Norwegian fjords at the present day, or along the bottom of the Black Sea where streams off the Caucasus mountains deposit gravel in the sea at considerable depths.

Bain[56], in 1955, and later in 1960[57], considered the conglomerates to be the equivalents of a parallel, linear pattern of gravels on a piedmont plain in which stream channels had been entrenched only slightly. There was a recurrent fill of the channels, followed by scour of the more mobile particles. He thought that the paystreaks showed an arrangement similar to that of tributaries converging downstream towards a major river flood-plain in the centre of an alluvial basin.

Instead of a radiating geometry to the lenses of banket, he saw a converging pattern. As a result, he envisaged the uplifted side of the basin to have been in the east and southeast and the movement of material towards the northwest, the opposite of almost all previous conclusions. He even alleged that the cross-bedding directions in the Main Reef Leader showed a northwesterly orientation, which was also contrary to all earlier observations.

The concept of transportation of debris by ice was revived by Wiebols[58] in 1955. The depositional area was considered to have been a vast peneplain bordering on a shallow inland sea, which was landlocked and of similar size to the Baltic or the Mediterranean seas. Sedimentation took place on the edge of an inland ice-sheet, which was comparable in size to the Gondwanaland ice sheet of Carboniferous age. The ice was the dominant medium of transportation, especially for the major reef horizons, which were seen as being composed of ground moraine or glacial boulder clay that was subsequently subjected to wave-action in a transgressing sea, the sand and pebbles being left behind on a peneplain as the ice-sheets retreated. Ice-flows from widely separated areas brought their own particular petrological mix, accounting for the conspicuous differences in composition between some of the reefs. Wiebols maintained that boulder clay, which had escaped wave-action, could still be seen as footwall argillaceous material below the Main Reef Leader and the Kimberley Reefs. Varved shales were also to be found in these footwalls. The erosion channels in the Main Reef Leader footwall were seen as drainage features through which the melt-waters of the ice masses had escaped. The payshoots were interpreted as eskers, long ridges of pebbly sand formed underneath the inland ice-sheet by watercourses. The gold content of the eskers was subsequently enhanced through milling by the transgressing sea. Contrary to the opinions of most other investigators, Wiebols doubted whether there had been frequent movements of uplift and subsidence, and he believed that the variations in grain-size were essentially a function of the distance between the inland ice-sheet and the sea.

Brock, Nel, and Visser[59] presented a paper in 1957 on the uranium deposits in the Witwatersrand Basin which they felt had been an extensive interior or intracratonic basin fed by a number of streams that had travelled no great distance from the source-area. The streams, which had entered on the northern and northwestern sides of the basin, had left fan-shaped deltaic remnants about their mouths. Deposition was in shallow water or subaerial, and was distinctly cyclic in nature with the fine-grained material having accumulated during sinking of the basin, and the coarse-grained during elevation of adjacent land-areas. The richest conglomerates were developed on planes of intraformational diastems, disconformities, and unconformities. In general, conditions were fairly cold and dry. In 1958, Nel[60] added an important observation to the effect that a portion of the basin rim coincided with the outer limb of a major anticline wrapped around the Vredefort dome, some 40 miles away. This was the first reference to the influence of regional folding on the limits and geometry of the basin.

On the basis of the very coarse average grain-size of little-rounded quartz in the Upper Witwatersrand quartzites, Fuller[61] wrote in 1960 that the mineral was probably derived from a local coarse-grained primary source of quartz. On the other hand, the mineralized conglomerates were well sorted and continuous, and pointed to long transportation under conditions of sustained equilibrium that permitted the development of extensive gravel sheets. The quartzites were poorly sorted, massively bedded, and commonly cross-stratified, suggesting that the basin filled rapidly from local sources. As a result, he proposed that the quartzites and the conglomerates had been derived from different sources. In Upper Witwatersrand times, the drainage pattern was effectively disintegrated by recurrent faulting, so that, only at intervals, were master streams established. These introduced the gold, uranium, and other minerals from sources outside the confines of the basin. In the same year, Koen[62], on the basis of the first quantitative mineralogical study carried out of the Witwatersrand reefs, concluded that they were formed in two pulses – the first produced an openwork gravel on wide alluvial plains, and the second led to the infiltration of sand into the pores between the pebbles. A transgressive beach subsequently spread out the gravel accumulations.

The first results of the major programme of sedimentological investigation, which was launched by the Economic Geology Research Unit, appeared in 1962 when Hargraves[63] published a paper on transportation directions in the East Rand. The bimodality of the cross-bedding azimuths he interpreted as indicating movement of material in a south-southeasterly direction and its subsequent redistribution by high tides flowing towards the northeast. The fanning of the cross-bedding directions was found to be of similar pattern to the radiating geometry of the paystreaks. In the following year, Steyn[64] reported on the first detailed sedimentological study carried out since the pioneering work of Pirow[25] in 1920 and of Reinecke[29] in 1927. The Livingstone Reef of the West Rand goldfield was found to be fan-shaped, with an apex in the northeast, the quartzite ratio being highest towards this apex, the pebble-size larger, and the roundness less pronounced. The

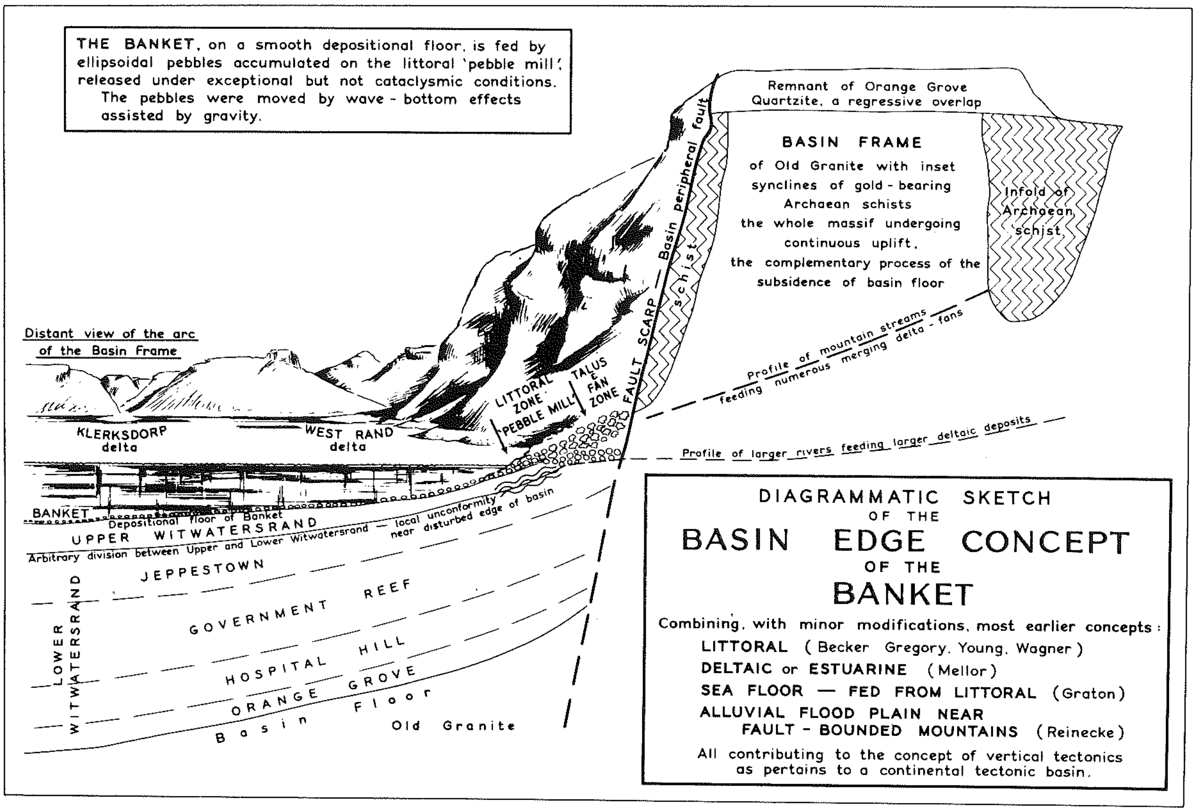

FIGURE 4 A pictorial conceptual model of the depositional environment of the Witwatersrand banket, as devised by Brock and Pretorius[66] in 1964. [reproduced by permission of the Geological Society of South Africa].

central main channel contained the higher gold values, and its location coincided with the axial direction of the major synclinal fold of the area. Cross-bedding in the channel was found to be parallel to the fold's direction of elongation. Transverse and longitudinal sandwaves and ripple-marks indicated both current-flow and wave-action, with an estuarine current moving from north to south and a weak longshore current from west to east. The sorting coefficients of the sands were found to be intermediate between those for a beach and a river, with a distinct tendency towards the latter. The type of cross-bedding pointed to a fluvial or deltaic environment and not to a beach. The paystreaks were observed to be arranged in a fan pattern typical of alluvial fans or marine deltas. Steyn concluded that the weight of the sedimentological evidence was in favour of the environment's having been that of a small delta formed where a river flowed directly from a highland into a sea or a lake. From the rates of change of certain of the properties of the sediments, he calculated that the apex of the delta had not been more than 7 to 9 km north of the position of the present outcrops.

Viljoen[65] published in 1963 what is considered to be the most extensive quantitative mineralogical study of the Witwatersrand arenaceous sediments that has yet been attempted. He examined many conglomerate and quartzite horizons in the East Rand, Central Rand, West Rand, and West Wits goldfields, and came to the conclusion that the micro-sedimentology gave strong support to the environment's having been that of a delta, the lower portion of which had been reworked by waves and currents under beach conditions. The submature matrix of the banket, with relatively large amounts of clay constituents, gave indications of a fluviatile origin. The degree of sorting suggested a fluviatile or beach situation. Viljoen identified separate deltas for the East Rand, Central Rand, and West Rand. Adjacent to the basin, elevated land occurred, from which gravels moved to the deltas by means of fast-flowing rivers. A systematic decrease in grain-size was apparent radially away each entry-point of material into the delta. The farther away from these entry-points, the more the material was reworked by littoral agencies. He found that the leucoxene, pyrite, arsenopyrite, zircon, and chromite were in hydraulic equilibrium, indicating that all of these minerals were of detrital origin. The hydraulic equivalent numbers showed that the pyrite had been laid down as pyrite, and not as black sands. The complete lack of oxidation of the detrital pyrite was taken as evidence of an atmosphere free of oxygen and of a cold climate.

The publication of the special volume on the Witwatersrand basin in 1964 by the Geological Society of South Africa saw a comprehensive synthesis and an attempt at reconciliation of the various theories by Brock and Pretorius[66]. Four distinct entry-points of material into the basin near Benoni, Krugersdorp, Klerksdorp, and Welkom were considered to be deltas formed on the basin-edge in structurally depressed portions of the rim between rising granite domes. Because of the major development of peripheral faults, the northwestern flank of the depository was a much more active source of sediments. The basin was bounded on all sides by land, and shallow-water conditions prevailed throughout the history of sedimentation. The skewness of the delta-shapes was ascribed to the effects of a longshore current flowing in a clockwise direction round the basin. In addition to the four main entry-points, it was thought that numerous small water-courses, talus slopes, and small merging delta-fans existed on the edge of the depository. Isopach maps were presented for the first time of the main groupings of strata in the Witwatersrand succession, and these unequivocally showed that the basin had been a shrinking feature with time. The Lower Division had occupied a larger area than the Upper Division. The basin frame underwent continuous uplift, causing a progressive advance of the zero isopachs towards the depositional axis. On the uplifted hinterland, remnants of Lower Division rocks were largely eroded to feed the Upper Division accumulations. Brock and Pretorius commented that: 'Seven or eight different hypotheses have been enunciated to explain this origin [of the banket]. Geological observations (including a preponderance of good observations) over a period of three-quarters of a century have not resulted in agreement'. The reconciliation that best fitted the facts was the one that they diagrammatically portrayed in Figure 4. The hinterland was separated from the depository by a fault-scarp of impressive dimensions along the peripheral fault zone of the basin. Immediately adjacent to the fault-scarp, talus and fan zones were formed at the mouths of major rivers debouching from canyons.

A pebble mill developed in the littoral zone at the base of the fans, and waves and longshore currents contributed to the distribution of pebbles over considerable distances parallel to the shore. The banket was laid down on a smooth floor fed by the littoral pebble-mill, the pebbles having been moved downslope from the shore by wave-bottom effects assisted by gravity. High rainfall and no vegetation characterized the overall environment. In two additional papers in the 1964 volume, Pretorius[67,68] stressed the observation that maximum gold concentrations occurred at a certain optimum distance from the shoreline. The Lower Division sediments, as presently exposed, had been laid down too far into the basin from the shore, while the Elsburg conglomerates, at the top of the stratigraphic column, represented too proximal a facies. He also drew attention to the fact that near-shore conditions on the southeastern side of the basin had not acted as host to the same assemblage of sediments as had been deposited on the more active, northwestern edge. Far less material had been contributed from the southeast, and very little gold had been associated with it, so that the economic potential of this limit of the depository was at a minimum.

In his two contributions to the volume, Winter[69,70] dealt with the main gold-bearing horizons of the northern and southeastern sections of the Orange Free State goldfield. He came to regard the general shape of the sedimentary units, the regular stratification, the variations in facies, and the relationships between facies as indicative of a shallow inland sea where the imprints alternated between deltaic, estuarine, beach, and even fluviatile environments. The elevated ground to the west moved eastwards with time, leading to the removal and redeposition of sediments. Material entered the basin from localized areas in the west and southwest, and there was a progressive northwards advance of the entry-points. Submergence kept pace with the influx of detritus. Owing to the periodic elevation of the source-area, cyclic sedimentation characterized the assemblage of strata. Slow upwarping to the south and east maintained a wave-cut surface, on which only the coarsest, heaviest, and most resistant particles were not swept away. As the shoreline receded from the land, a marginal, terminal, or regressive conglomerate was formed, as, for example, the Basal Reef. The smooth surfaces marked marginal unconformities, with their graded profiles typical of an epineritic environment. The payshoots in this reef were considered to be the products of longshore currents in the inland sea. Winter made the first comments on the pattern of coarse buckshot pyrite being closest to the shore, gold somewhat farther out, and uranium still farther. The displacement between the zones of maximum gold and uranium mineralization later came to be recognized in most of the other goldfields. A long period of sorting was necessary to produce the Basal Reef. Where a basal conglomerate developed on a rapidly transgressing shoreline, as in the case of the Leader Reef, the time of sorting was much shorter, so that such reefs assumed a lower economic potential than terminal conglomerates. The Kimberley Reefs were classified as typically fluviatile. Channels denoting transitional marine and continental environments were observed to occur only in the Kimberley strata. The Elsburg conglomerates were considered by Winter to be subsidiary deltaic deposits, because the reefs were clustered into vertically superimposed groups. The regular and sheetlike erosion of the marginal sediments was taken as indicating a shallow, aqueous environment. Deltaic and fluviatile conditions were concluded to have prevailed when the basin was at its smallest. For the rest of the time, a neritic environment existed, in which winnowing and sorting agents were optimally operative.

In the following year, Winter[71] looked at the Vaal Reef of the Klerksdorp goldfield, and found that the adbundance of trough cross-bedding was highly suggestive of a fluvial or deltaic environment. However, the absence of discordant channels, and the presence of mudstones, mudcracks, clay pellets, and slumped trough foresets mitigated against the fluvial interpretation. In addition, regular fluted scouring, regular current pattern, slight divergence in current directions, widespread narrow sheets of small-pebbled gravels, longitudinal elongation of sand-bodies, and a shallow-water regime, all favoured a water-covered deltaic environment. Mud galls in the upper portion of the Vaal Reef showed that no winnowing by wave-action had taken place. The Kimberley Shales, stratigraphically above the Vaal Reef, were stated to be of marine origin, having been formed on the basinward side of the delta. The still higher Elsburg reefs were seen as the products of fluvial or fluvio-deltaic conditions. Winter recognized distinct similarities between the Vaal Reef and the Pennsylvanian-age Sharon conglomerate of Ohio, which has been interpreted as of alluvial or deltaic origin. The Vaal Reef represents a facies somewhat more basinward than that of the Sharon formation.

In 1965, the results appeared of another outstanding sedimentological study. This was of the Kimberley Reef in the East Rand goldfield, and was undertaken by Armstrong[72]. He found abundant evidence for a continental and fluvial origin of this reef, despite the frequency with which arguments had been advanced in the past to the effect that a neritic environment had been in existence. An extensive subsiding pediplain developed, with features similar to that of a valley-flat environment. The floor of this valley was structurally deformed, and a distinct relationship developed between the orientation of the reef bodies and the paleotopography of the floor. The bulk of the reef was derived from the erosion of the floor. The conglomerate-filled channels ran parallel to the depositional slope. Oscillation ripplemarks showed the prevalence of shallow-water conditions, mudcracks pointed to subaerial exposure at times, and the imbrication of the pebbles was typically that of a fluviatile environment.

Knowles[73] published in 1966 the results of another detailed sedimentological examination, this one being of the Ventersdorp Contact Reef in the West Wits goldfield. The reef thickness, percentage conglomerate, pebble composition, pebble roundness, maximum pebble-size, size distribution, cross-bedding, pebble imbrication, and grain orientation led him to believe that this banket, at the very termination of Witwatersrand sedimentation, was the product of an alluvial fan that extended from a fault scarp in the northeast into an inland sea. The currents flowed south-south-westwards down the fan. Penecontemporaneous folding of the paleoslope controlled the distribution and deposition of the coarser material. Depositional gravels formed in the depressions and lag gravels on the elevations of the floor. The cross-bedding measured was typical of a fluviatile environment, as was the style of pebble imbrication. Observations were made of both a transporting current down the fan and a longshore current operative in the inland sea.

In 1966, Pretorius[74] produced a synthesis of the detailed sedimentological work that had taken place during the previous five years. He stated that it was generally agreed by all the investigators that the source of the sediments and the gold lay to the northwest of the basin, that the material was transported by rivers from the source-area to the depository, that the conglomerates, gold, and uranium were laid down close to the edge of the basin, and that the sediments had there been reworked and concentrated by wave-action and longshore currents in a closed basin, which was either a shallow inland sea or a lake. Reconciliation of the various interpretations produced a picture of a goldfield as most likely having been a wet alluvial fan or a fluvial fan that had developed at the point of discharge of a major river into the basin, the long axis of which trended east-north-east. The sediments were deposited on the fan by the river, and were later reworked by waters from both the river and the lake or inland sea. The fans all had varying degrees of asymmetry caused by the elongation of one lobe by longshore currents flowing in a clockwise direction round the basin. An uplifted highland surrounded the intermontane basin, and the interface between the two terrains was formed by a series of peripheral faults of major dimensions. Movement along the bounding faults caused recycling of the apices of earlier fans into the sediments of later periods of sedimentation. Four rivers were identified – one feeding the Orange Free State goldfield, a second the Klerksdorp goldfield, a third the West Wits, West Rand and western portion of the Central Rand goldfields, and a fourth the eastern section of the Central Rand, the East Rand, and the Evander goldfields. The strata of each goldfield represented the aggregate of a number of superimposed fluvial-fans formed at the mouth of the same river. As the basin grew smaller with time, so a regressive relationship developed between the mean positions of successive fans in the Upper Division. Present-day analogues of such an environment appeared to be more the alluvial fans and delta-fans of the foothills of the Alpine and Himalayan mountain fronts, with their much higher rainfall, than the fans of the arid Basin and Range Province. In this paper, Pretorius introduced two new concepts – identification of local depositional conditions according to fan facies, and employment of energy-levels as controlling factors in the nature of the sedimentary responses to the varying depositional processes. The conglomerates, grits, and quartzites had formed preferentially in the central and inner intermediate portions of the fanhead and the upper midfan, and the fine-grained quartzites, argillaceous quartzites, shales, and carbonaceous material in the outer intermediate and marginal portions of the lower midfan and fanbase. The sediments of the Lower Division were essentially products of fanbase and distal lacustrine environments, and those of the Upper Division of lower fanhead, upper midfan, and proximal lacustrine conditions. Goldfields developed only in high-energy regimes about the entry-points of the fluvial systems into the basin, while paystreaks were high-energy major stream channels on the fluvial fans.

In the only major publication that has so far appeared on the Evander goldfield, Tweedie[75] wrote in 1968 that the evidence favoured marine rather than fluvial conditions for the laying down of the Kimberley Reef. Uplift occurred to the east of this area. Material moved from the east-northeast, while longshore currents flowed from the west-southwest. Shoaling conditions and barrier beaches developed in the west and south, separating the Evander basin from the East Rand depository, which two goldfields were not connected from late Main-Bird times to the time of formation of the Kimberley Reef. The two areas might have been reconnected after the accumulation of the Kimberley Reef, when longshore currents swept sands eastwards from the East Rand entry-point.

In his book on the geological history of Southern Africa, published in 1969, Haughton[76] classed the Witwatersrand depository as an intracratonic closed basin, comparable in size to Lake Victoria. Rivers deposited the debris from surrounding highlands in deltas, at the edges of which waves and currents caused partial redistribution, particularly near the shore. In the Upper Division, differential tectonic movements produced local disconformities. Transgressions and regressions were partly due to climatic variations. Channels were cut and filled near the major feeding streams. Greater volumes of material were transported to the northwestern side of the basin, but by Upper Division times the main points of entry lay at only a few places around the periphery.

In 1969, Knowles[77] concluded that the Basal Reef of the Orange Free State goldfield had been deposited by fluvial agencies, in the form of channels and stream floods, on the central and lower portions of an alluvial fan extending into an inland sea. The sediments spread over the paleoslope by the lateral accretion of gravel point-bars. Later in the same year, on the completion of a comprehensive and valuable sedimentological investigation of most of the reefs in the same goldfield, Sims[78] came to the conclusion that all the products could be seen of the interaction between fluvial, valley-flat-pediment, delta-fan, littoral, and quasi-neritic lacustrine environments proximal to the entry-point of a fluvial system into a landlocked continental sea. Throughout the depositional history, constant adjustments, involving vertical tectonics along continuously active marginal faults, influenced and controlled sedimentation, gradually reducing the size of the basin and producing unconformities. The reef horizons were formed under essentially degrading conditions in the wake of the tectonic episodes, while the normal members accumulated in aggrading regimes with equilibrium conditions when the rate of subsidence was equal to the rate of sediment feed. The auriferous bodies were restricted to the margin of the basin, and always developed on unconformities. The Basal Reef was introduced from the southwest by a river which deposited on a delta-fan under shallow-water and intermittently subaerial conditions. It became the product of prolonged degrading and incising of the footwall by meandering streams which simultaneously introduced the gold-bearing detritus. Many distributaries migrated to and fro across the depository on a planar surface of erosion. Winnowing currents trended north-northwestwards. Sims indicated that the Leader quartzites were channel deposits, the Middle Reef fluvial channel accumulations, the lower Kimberley Reefs fluvio-deltaic sediments, the upper Kimberley Reefs fluvial deposits with deep erosion channels, and the Elsburg reefs the products of a rapidly aggrading delta-fan adjacent to a very active boundary fault.

The most significant study of the uranium present in the Witwatersrand reefs was carried out by Liebenberg[79] and published in 1955. He showed that it occurred in two forms, as thucholite associated with carbon and as detrital uraninite grains. The latter variety was gradually concentrated with other black sands in streams that discharged into marine placers. For the uraninite to survive during subaqueous transportation and deposition, Liebenberg concluded that a nonoxidizing atmosphere must have prevailed. Another notable contribution was made by Koen[62] in 1961, in which he stated that the well-rounded appearance and close sizing of the uraninite grains could be taken as strong indicators of reworking by vigorous wave-action. He believed that compact nodules of the mineral formed on the muddy floors of extensive marshes or shallow lakes, and that these nodules were subsequently churned up by the waves during the initiation of a new cycle of sedimentation whereby the uraninite became re-distributed, was mixed with the normal sediments, was sorted, and then was deposited with the sand and gravel.

In 1949, Sharpe[45] reported that carbon was common on the peneplaned depositional floors beneath the Main Reef, Main Reef Leader, Hangingwall Leaders, May Reef, and Black Reef of the East Rand goldfield. It was also present in channel and lagoonal deposits. From this, he concluded that the carbon was most apparent in those horizons that formed along shorelines and between tides, in stream channels, and in muddy lagoonal deposits, the precise horizons that would favour the development of bacteria and possibly algae. He put forward that the carbon granules and other forms of carbon found in the banket might be the remains of some of the earliest forms of life. However, he felt that the association between gold and carbon was purely coincidental. In the following year, Fletcher[80] drew attention to the fact that certain elemental marine plants can concentrate radioactive substances in their systems, and suggested that the uranium-bearing Carbon Leader of the West Wits goldfield might have formed from such organic matter in a marine environment where the gold was concentrated under water. In 1951, Davidson and Bowie[81] disagreed with these ideas, and wrote that the evidence conclusively proved that gaseous hydro-carbons of hydrothermal origin had undergone polymerization around pitchblende nuclei. As a result, there was a consolidation of hydrocarbon gel, with an accompanying coagulation and floccu-lation of colloidally dispersed pitchblende into blebs. Two years later, MacGregor[82] suggested that the Witwatersrand basin had been fringed with algal peat bogs. The waters entering these swamps carried nitrates, chlorides, and sulphuric acid, which acted as solvents of the gold and uranium. Reducing conditions induced by dead organic matter in the stagnant waters precipitated the gold and uranium. Torrential floods washed out the peat, and carried it far out into the lake where it absorbed still more uranium and sank to the bottom. Miholic[55], in 1954, supported Sharpe's[45] earlier contention that the carbon was the product of organisms belonging to the oldest, if not the first, forms of life that appeared on Earth late in the Archean. A rich growth of vegetation con-centrated the uranium under anaerobic conditions.

Columnar thucholitic carbon was reported by Liebenberg[79], in 1955, not to be as common as the carbon granules. His belief was that organic remains, probably of algae, in various stages of decomposition in marine bottom-muds generated a variety of hydrocarbonaceous materials, in-cluding methane, which were polymerized by radioactive emanations. He noted that the amount of hydrocarbon increased upwards from the Dominion Reef to the Black Reef, suggesting that there was a gradual proliferation of biological activity. Viljoen[65] subscribed to Liebenberg's concepts, and added, in 1963, that this enhanced activity probably took place on fluvial or delta-flats after the main influx of reef material. Brock and Pretorius[66], in the following year, concluded that the pattern of interlaced gold in carbon seams was reminiscent of algal structures. They con-sidered that the biogenic material had accumulated in a lagoon or marsh, as part of an isolated embayment on a delta.

The year 1965 saw the first of the publications dealing with detailed microscopic and chemical studies of the carbon, which investigations led to more and more definite conclusions that the carbon was of biological origin. Snyman's[83] work revealed structures in the thucholite very similar to certain algal and fungal features in sapropelic coals, and he concluded that the thucholite represented highly coalified algae. He saw the uraninite as being precipitated from solution as a result of algal activity. In 1966, Pretorius[74] put forward the proposal for the first time that the carbon-bearing conglomerates, with varying quantities of fly-speck carbon granules in the matrix, were the product of the intermixing of algal mats laid down at the end of a preceding cycle of sedimentation and of gravels formed in the initial stages of the succeeding cycle. The first carbon isotope studies were reported on by Hoefs and Schidlowski[84] in 1967. Their results indicated that the Witwaters-rand carbon was similar to sedimentary organic carbon of known biogenic derivation, mainly of the bituminous type. It was thought that the carbonaceous material was genetically related to oil rather than coal. They concluded that the waters of the Witwatersrand depository must have harboured a rich development of bacterial and algal life. In the same year, Prashnowsky and Schidlowski[85] added that amino acids and mono-saccharides had been detected in the carbon of the Basal and B reefs of the Orange Free State goldfield. The only explanation that could be offered for their presence was that life processes must have been operative in the basin. Electron microscope studies also indicated the development of globose aggregates resembling cell colonies.

The years between 1949 and 1969 can be summarized as representing the most productive period in the history of Witwatersrand geology. The large number of objective investigations during Phase 4 removed many of the subjective elements from discussions on the nature of the depositional environment of the Witwatersrand sediments. Theories supporting wet alluvial fan, pediment, fluvial fan, valley-flat flood-plain piedmont-plain, delta-fan, estuary, beach, and neritic off-shore environments were all advanced during the period. However, an ever-increasing number of investigators came to appreciate that many of the features observed showed conditions transitional between continental and marine, and between fluvial and littoral. At the time of deposition of different reefs, different conditions prevailed, so that no one particular explanation could be offered that would satisfy all the features of all the reefs. The overall environment could best be described as fluvio-deltaic-littoral. The most satisfactory present-day analogies were believed to be represented by conditions prevailing in the valley-flats below the Alpine and Himalayan mountain-fronts and in the Basin and Range Province of the western United States.

During these twenty-one years, sedimentology assumed a justifiably important role in all serious attempts to unravel the problems of the depositional history. Cyclic sedimentation came to be recognized as the normal manner of accumulation of material. Reworking by wave-action and longshore currents was also seen to be an essential process in the formation of the reefs. The asymmetry of the delta-fans pointed to a clockwise motion of the currents in the intracratonic, closed basin, which took the form of a landlocked lake or shallow-water inland sea. Although glaciers were considered as a possible transporting medium for bringing the material from the source-area to the depository, the weight of the sedimentological evidence pointed strongly to rivers filling this role. The conglomerates were interpreted as having accumulated in two separate pulses of sedimentation – the first, of a higher energy-level, forming an openwork gravel, and the second, of an intermediate energy-level, distributing sand that infiltrated between, and covered, the pebbles to form the matrix of the banket and the quartzitic hangingwall. The restriction of payable gold- and uranium-bearing horizons to unconformities and breaks in sedimentation became an accepted fact. It was also determined that the maximum concentrations of gold occurred at a certain distance down the delta-fan and the greater accumulations of uranium somewhat farther into the basin. The importance of peripheral faults, particularly along the northwestern edge of the depository was clearly established, differential movement between the uplifted source-area and the subsiding basin taking place along these dislocations. It also was put forward that regional folding had contributed to the relative elevation and depression of hinterland and depository. At least four major points of entry of material into the lake or inland sea were identified, at each of which a large delta-fan developed at the mouth of a river. The rivers flowed from northwest to southeast.

The presence of uranium and carbon was taken into consideration in deciphering the depositional environment. Evidence from uraninite confirmed the conclusions drawn for the conditions under which the gold was concentrated. Sedimentological and chemical work removed the element of speculation about the origin of the carbon. By the end of Phase 4 there remained little doubt that it had formed from bacteria and algae which had flourished in the waters at certain times and which had precipitated or absorbed substantial amounts of gold and uranium that were thought to have entered the basin in solution, as well as in the form of the detrital particles that had concentrated in the conglomerates.

THE PERIOD BEGINNING IN 1970

The results of a very detailed and extensive sedimentological study of the Vaal Reef in the Klerksdorp goldfield were presented by Minter[86] in 1972. It was shown that a structurally determined entry-point had existed to the northwest of the area, and that a shoreline feature at a relatively short distance into the basin had created the conditions favourable for the formation of the Vaal Reef. The footwall of this stratum built out as a delta with a regressing shoreline down the paleoslope towards the southeast. As the regression became more extensive, so a vast, subaerial, wind-blasted sand-flat came into being. The shoreline then transgressed, truncating the deltaic plain to a very regular erosion surface, and thus formed an angular unconformity of wide extent. At the same time, estuarine braided channels were incised in a meandering pattern in a generally southeasterly direction. A protracted period of deposition of the Vaal Reef was marked by a mature pebbly quartz arenite and basal algal growth. The material filled irregularities in the erosion surface and spread between the channels to form a dendroidal belt of sediments carrying gold and uranium. The southeastwards migration of lunate dunes over a non-accumulating surface for a long time produced the patterns of mineral distribution. Continued transgression deepened the environment and caused the shoreline to advance, during which the pebbly arenites were cleaned up. The clay galls associated with the reef point to fluviatile conditions that existed in a de-oxygenated lagoon that was ultimately destroyed by the Vaal Reef transgression. The presence of slightly waterworn dreikanters suggested proximal, wind-blasted environments before the reef was laid down. Two separate entry-points were present, within several kilometres of each other, and differing pebble assemblages and gold contents developed about these discrete localities. The one to the west brought in very little gold. An offshore current moving to the northeast buried the Vaal Reef beneath a wedge of sediments prograding from the southwest. Whereas the Vaal Reef was seen as the product of a transgression, Minter considered the Kimberley Reefs to have been formed as fluvial gravels in a regressive environment and the Ventersdorp Contact Reef as an alluvial fan, also in a regressive circumstance.

In 1973, Antrobus[87] revised his ideas of twenty years earlier, coming to the conclusion that the large mass of information that had been gathered in that time no longer supported his original idea of the reefs representing residual detritus that accumulated on a pediment. Instead, he believed that they were formed of fluviatile gravels, which had been laid down on a smooth erosion surface that had been bevelled to the base-level of a river. Cross-bedding showed a radial distribution of the gravels from an entry-point on to the erosion surface. He saw an analogy in the coastal plains of the eastern United States where the Cretaceous-Tertiary Brandywine formation had formed under fluviatile conditions after spreading out from a hinge-line between the piedmont and the coastal plain in the area now covered by the Delaware and Potomac rivers.

Steyn[88] reported, in 1974, on the investigations that had been undertaken of the Bird Reefs of the West Rand goldfield. The White Reef was interpreted as a compound coalescing dispersal fan on a piedmont-plain near the head of a delta, which formed as the valley-fill of a major river prograding into the Witwatersrand Basin. During dry periods in this fluvial environment, wind-action produced pebble pavements. The portion of the original conglomerates that are now preserved belonged to the fanbase environment that merged into the upper valley flood-plain. A high concentration of heavy minerals accumulated as lag channel deposits in the more permanent distributary channels on the fan, while the rest of the gravels were deposited by shifting braided streams. The poorly mineralized conglomerates were laid down high upslope, near the apex of the compound fan, as channel bar deposits of braided streams oversupplied with sediments. Farther down the slope, where the currents were undersupplied with bedload materials, water continuously washed over thin sheets of sediments causing extensive winnowing and concentration over floor-highs in the channels. The payable reefs, therefore, represented residual lag gravels in the beds of the larger streams.

Convincing evidence in favour of the biogenic origin of the carbon was presented in 1973 by Hallbauer[89]. Through electron-microscope studies, he was able to observe that each column of carbon was surrounded by a thin membrane, and contained inside an irregular framework of hyphae-like filaments. Gold encrustations were abundantly developed on these filaments. He found the fly-speck carbon to be similar in size and shape to living fungus spores, and these also had inclusions of gold. He interpreted the carbon seams as the fossilized remains of lichen-like plants and the carbon granules as the reproductive form of the plant.

SUMMARY

From an analysis of the 90 significant contributions to the geological literature on the depositional environment of the Witwatersrand conglomerates, carbon seams, and other sediments, which have been reviewed, the following events and developments are considered to be the ones which contributed most towards helping to understand the conditions under which the gold- and uranium-bearing reefs were formed:

1896 suggestion that carbon might have been formed by 'organized beings' (Garnier[10])

1897 comparison of conglomerates with auriferous beaches of New Zealand and the northwestern United States (Becker[7])

1908 recognition that payable reefs are associated with breaks in sedimentation (Gregory[14])
comparison of carbon with present-day gold-bearing fresh-water algae in streams in California (Spilsbury[31])

1909 recognition of paystreaks of richer conglomerates (Young[17])

1911 report on first systematic and comprehensive investigation of geology of Central Rand and West Rand; recognition that not all reefs were formed under the same depositional conditions; first proposal of deltaic environment (Mellor[19,20])

1915 conclusion that general coarsening of sediments stratigraphically upwards due to hinterland advancing progressively into basin (Mellor[21])

1916 suggestion of reworking of reefs by wave-action; of recycling of Lower Division sediments into Upper Division (Mellor[22])
suggestion that conglomerates might have formed in alluvial valley-flat, such as that occurring in plains below fault-bounded Himalayan mountain-front (Evans[24])

1920 report on first sedimentological studies; recognition of two pulses (first openwork gravel, second infiltrating sand) to form conglomerates; first suspicion of radioactive material in reefs (Pirow[25])

1924 presence of uraninite proved in conglomerates (Cooper[30])

1926 proposal that elements of fluviatile, estuarine, deltaic, and littoral environments can be recognized in different reefs (Du Toit[27])

1927 first use of contoured assay plans to delineate paystreaks; recognition of fan-shaped pattern of paystreaks in East Rand, of two interfering directions of paystreaks at right-angles to each other on Central Rand, of braided stream patterns, of lobes on fans, of entry-point of material north of Benoni; suggestion of ice-sheets as being transporter of sediments rather than rivers; first substantive arguments for valley-flat, fluvial flood-plain environment (Reinecke[29])

1930 first report on use of cross-bedding to determine paleo-current directions; recognition that proximal facies stacked on distal facies stratigraphically upwards (Reinecke[34])

1931 introduction of concept of delta-fan instead of previously assumed oceanic delta (Mellor[37])

1936 suggestion of conglomerates having formed on alluvial fans in piedmont environment (Johnson[40])

1938 recognition that major conglomerate horizons occur on disconformities (Roberts and Kransdorff[41])

1940 proposal that certain conglomerates were formed from eluvial scree on arid pediment (De Kock[43])

1949 first description of ubiquitous cyclic sedimentation in Witwatersrand Sequence; proposal that carbon occurs on those stratigraphic horizons where conditions could have favoured presence of bacteria and algae (Sharpe[45])

1954 proposal that basin completely surrounded by land; identification of facies changes in reef horizons with respect to distance from basin-edge; suggestion that Witwatersrand be compared with Basin and Range environment of western United States (Antrobus[51,52])

recognition of separate, discrete entry-points of material for different goldfields; suggestion that depository is intracratonic basin (Brock[53])

1955 first comprehensive description of nature of uranium mineralization (Liebenberg[79])

1958 observation that geometry of basin influenced by folding (Nel[60])

1962 first report on re-introduction of sedimentological methods of investigation (Hargraves[63])

1963 first comprehensive macro-sedimentological investigation (Steyn[64])

first comprehensive micro-sedimentological investigation (Viljoen[65])

1964 first attempt at overall synthesis of previous work; first compilation of isopachs to outline geometry of basin; recognition of clockwise direction of movement of longshore currents; identification of confinement of locations of goldfields to synclinal downwarps between rising granite domes (Brock and Pretorius[66])

recognition that southeastern edge of basin more passive than northwestern, that minimum amount of sediments introduced from this side, that no significant amounts of gold brought in from southeast (Pretorius[68])

recognition of optimum zone of uranium mineralization as lying somewhat basinward of zone of maximum gold mineralization (Winter[69,70])

1965 first microscopic identification of possible algal origin of carbon (Snyman[83])

1966 first use of conceptual process-response models in synthesizing Witwatersrand data; employment of principle of energy-levels as measures of variations in depositional environments; proposal that goldfield represents higher-energy fluvial fan rather than lower-energy conventional delta-fan; design of standardized sedimentological investigation to produce maximum information; suggestion that carbon-bearing conglomerate result of breaking up of algal mat formed at end of preceding cycles by pebbles at beginning of succeeding cycle (Pretorius[74])

1967 carbon-isotope studies used to determine origin of carbon (Hoefs and Schidlowski[84])

chemical identification of biogenic derivation of carbon (Prashnowsky and Schidlowski[85])

1972 report on first comprehensive sedimentological study of whole goldfield as a single entity (Minter[86])

1973 detailed electron microscope investigation of carbon definitely establishes algal origin; suggests lichens might have fixed gold and uranium (Hallbauer[89])

1974 second attempt at overall synthesis of previous work (Pretorius[90,91])

The progressive changes in ideas concerning the nature of the depositional environment and the various conditions that prevailed in it have been summarized in Table 1.

TABLE 1
THE PERCENTAGES OF AUTHORS WHO FAVOURED DIFFERENT TYPES OF DEPOSITIONAL ENVIRONMENTS FOR BANKET DURING VARIOUS PHASES OF MINING HISTORY

Environment	Percentage of Authors					
	Phase 1 1886 – 1906	Phase 2 1907 – 1927	Phase 3 1928 – 1948	Phase 4 1949 – 1969	Phase 5 1970 –	Average 1886 – 1974
neritic	19	8	4	2	—	6
littoral	63	43	26	28	30	38
shoreline delta	12	33	29	16	—	18
shoreline fluvial fan	—	—	—	17	37	11
coastal fluvial	—	2	—	4	9	3
interior fluvial	6	14	32	22	11	17
interior desert	—	—	9	11	13	7

The trends in speculations and observations over the years are readily discernible in the table. The neritic environment was popular only during Phase 1, thereafter fading rapidly until there are no proponents of it at the present time. Elements of a littoral regime have been conspicuously present at all times, and the reworking of the conglomerates by wave-action and currents has generally been considered to have taken place on a beach, whether on an open ocean, an inland sea, or an intermontane lake. This environment received most support during Phase 1 and then drew progressively less adherents up to Phase 3. Thereafter, the littoral component was again incorporated into more and more hypotheses. The conventional delta gained its largest number of proponents in Phase 2. As it became less accepted, so it was replaced by the fluvial fan environment, which, today, has the largest percentage of supporters. Fluvial deposits on a coastal plain have never attracted many advocates. Interior fluvial processes in a flood-plain or valley-flat system have always had strong supporters, particularly during Phase 3. The number of investigators has been growing steadily since Phase 3, who have given preference to an inland desert environment embracing alluvial fans, bajadas, and pediments. Opinions over the past 89 years, in general, have favoured the littoral environment, with the deltaic and interior fluvial regimes next in popularity.

Only in Phase 1 was there a marked tendency to interpret the depositional conditions attending the laying down of the conglomerates as being restricted to one environment only. Geologists have usually regarded the Witwatersrand sediments as the products of at least two interactive regimes. The preferred combinations over the years have been the following:

Phase 1 (1886-1906): littoral + neritic
Phase 2 (1907-1927): shoreline delta + littoral
Phase 3 (1928-1948): interior fluvial + shoreline delta + littoral
Phase 4 (1949-1969): interior fluvial + shoreline fluvial fan + littoral
Phase 5 (1970-1974): interior desert + shoreline fluvial fan + littoral

TOWARDS A POSSIBLE RESOLUTION

Ten years after the *magnum opus* of the Geological Society of South Africa, on the geology of the Witwatersrand Basin and its contained deposits of gold and uranium, the time seemed appropriate to attempt a synthesis of all the work that had taken place since the appearance of the publication. The substantial amounts of data that had been gathered during extensive and systematic studies of the quantitative sedimentology, mineralogy, and geochemistry of the banket and carbon seams had either reinforced or undermined the theories that had been put forward in 1964 concerning the nature of the depositional environment. The generally accepted model required certain modifications. These were coordinated in 1974 in two papers by Pretorius[90,91] who attempted to resolve the differences of opinion that were becoming lesser in number and smaller in magnitude. After almost 90 years, there were signs that the beginnings of a consensus were being reached by the majority of geologists working on the problems of the Witwatersrand, although there still remained a small group of dissenters whose voices could not be ignored.

It would now appear that the Witwatersrand depository was a intermontane, intracratonic, yoked basin with a fault-bounded northwestern edge and a gently downwarping more passive southeastern boundary. The enclosed basin was at least 350 km long in an east-northeasterly direction, and 200 km wide in a north-northwesterly direction. The structural environment resembled that of the Basin and Range Province, but a far wetter climate prevailed. The basin was a shallow-water lake or inland sea, no connexion to an open ocean having yet been found. The depository became structurally more unstable with time, and a pattern of interference folding produced structural depressions and culminations both on the rim and within the depository. The various goldfields developed in downwarps between basement domes. The northwestern side was episodically but continuously rising, causing the basin-edge to advance progressively farther towards the depositional axis. The final depository was smaller than the original, so that, overall, the sediments were laid down in a shrinking basin. Conditions were generally transgressive in the Lower Witwatersrand Division and generally regressive in the Upper Division. Second-order transgressions and regressions were superimposed on these primary trends. Between the base of the Lower Division and the base of the Upper Division, the edge of the basin moved southeastwards by 60 km, and the depositional axis by about 10 km.

A high-energy transfer system from the source to the depository took the form of a relatively short, linear fluvial array. From the areal geometry of the different stratigraphic horizons, the patterns of facies variations, the trends in the changes of grain-sizes of sediments, the directions and patterns of paleoflow, the nature of the environmental indicators, and the distribution of heavy minerals, it would appear that a goldfield is a fluvial fan or fan-delta that was formed where the river system debouched into the lake via a canyon cut through the high ground to the northwest of the peripheral faults. In this type of environment, there were far

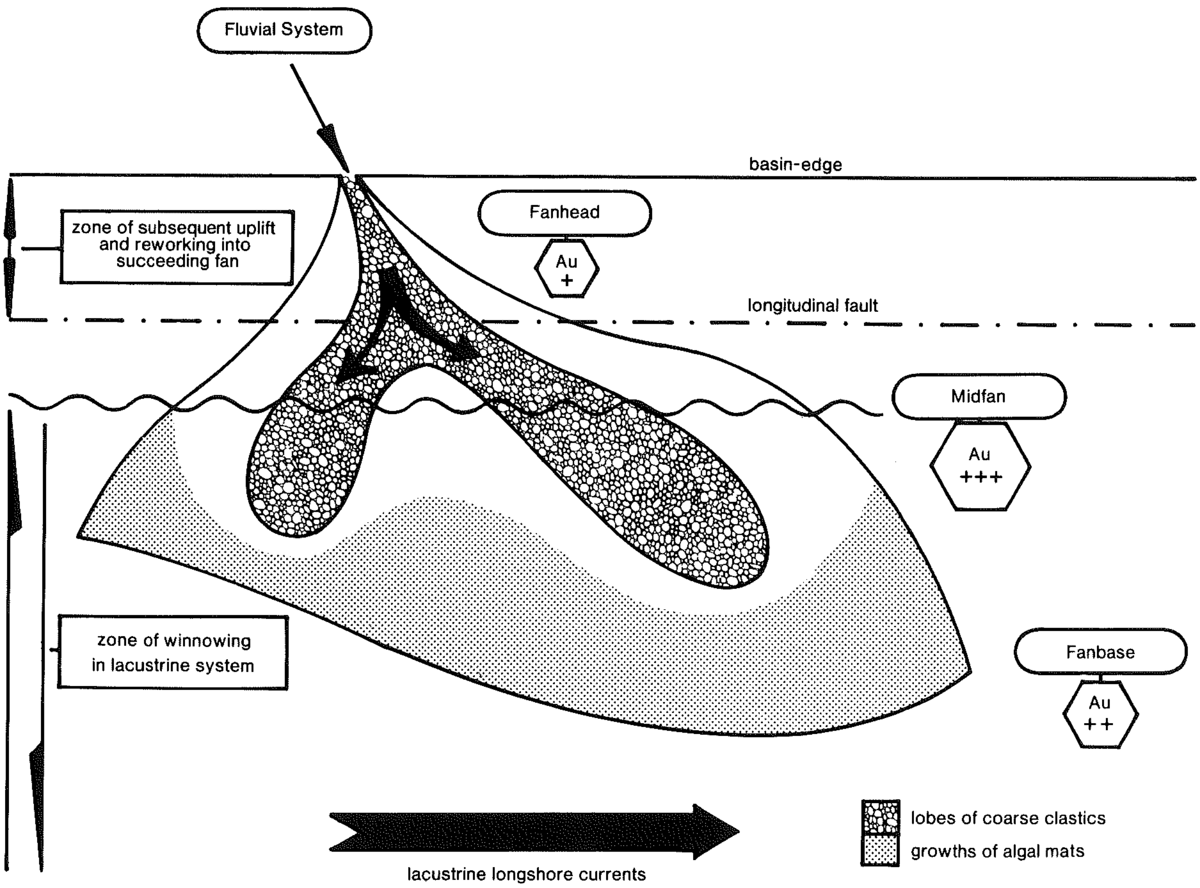

FIGURE 5 A conceptual model of a Witwatersrand goldfield as a fluvial fan developed at the mouth of a major river flowing from a source-area in the northwest and debouching into a shallow-water, intermontane, intracratonic lake over a peripheral hinge-line constituted by faults parallel to the depositional axis, as devised by Pretorius[91] in 1974. The general geometry of the fan, the various fan facies of deposition, the locations of coarse clastics and algal mats, the arrangement of varying zones of enrichment in gold, the portion of the fan subjected to transgression and winnowing, and the clockwise flow direction of the longshore currents in the lake are shown.

greater amounts of water than on a typical alluvial fan and the energy-level was higher than that on an oceanic delta. After emerging from the canyons, the rivers flowed short distances over a piedmont plain and then dispersed through a braided-stream pattern into the basin. The fluvial fans were restricted to the northwestern margin of the depository, and some of them coalesced in their more distal parts, leading to the impression of extensive sheets of uniform gravel. The largest of the fans was that constituting the East Rand goldfield, which measured 40 km in length down the central section from the apex to the fanbase, 50 km in width in the midfan section, and 90 km in width in the fanbase section. The western margin of this fan was 45 km long and the eastern flank 60 km. Six fluvial fans have so far been discovered – those constituting the Orange Free State, Klerksdorp, West Wits, West Rand, East Rand, and Evander goldfields. The original Central Rand, on which the Main Reef conglomerates were discovered, would seem to be a geographical entity only, since, geologically, it represents the coalescence of the eastern part of the West Rand fan and the western part of the East Rand fan.

The gold and uranium mineralization has been recognized to occur in five forms: (i) in the matrices of the conglomerates, (ii) in heavily pyritic sands filling erosion channels, (iii) on quartzites along a plane of unconformity between successive cycles of sedimentation, (iv) on shales along planes of unconformity, and (v) in carbon seams on, or adjacent to, planes of unconformity. The three last-mentioned types of reef were formed in the terminal stages of one cycle of sedimentation, and the first-mentioned two in the initial stages of a succeeding cycle. The gold and uranium were transported as detrital particles and in solution as chloride- and cyanide-complexes. Concentration took place physically, through gravity settling and subsequent winnowing by wave- and current-action, and biochemically through interaction between the gold and uranium and the algal or lichen colonies that preferentially developed about the mouths of the major rivers, in the quieter-water conditions on the margins and fanbases of the fluvial fans, and at the end of certain cycles of sedimentation.

The conceptual model of a typical Witwatersrand goldfield is portrayed in Figure 3. The apex of the fluvial fan was located along the tectonically unstable basin-edge where repeated uplift of the source-area side took place along longitudinal faults. The fanheads of earlier fans were thus uplifted and reworked into later fans, while the midfan and fanbase sections were structurally depressed and thereby preserved. The downward displacement of the midfan and fanbase also caused transgression of the lake waters, producing winnowing of the fines and lag concentrations of the heavier minerals. Longshore currents moved the finer sediments farther away from the entry-points to form asymmetrical fans owing to the clockwise movement of the water in the depository. The typical fluvial fan had two main lobes in which were located a larger number of braided-stream channels, thicker and coarser clastic sediments, and higher concentrations of detrital gold and uranium. The material that was laid down between the lobes took the form of sands, silts, and muds, similar to that which accumulated on the fan margins and base. Conditions under these lower-energy regimes at times provided the optimum environment for the growth of algae or lichens, which took the form of thin algal mats. The gold was of too fine a grain to settle in the fanhead facies. The highest concentrations took place in the midfan lobes, with the peak of uranium mineralization a little farther down the slope than the peak of the gold. The energy-level dropped too low to permit the transportation of detrital gold to the fanbase section. However, the gold and uranium that were in solution did interact with the biogenic material that was present in the low-energy environments.

A fluvial fan was built up in a series of pulses of sedimentation, which started with progradation during regression, went through aggradation during transgression, and ended with degradation during stillstand. These three stages constituted a single cycle of sedimentation. A new cycle was initiated through tectonic adjustment along the longitudinal faults. Such adjustment produced a steepening of the paleoslope, with the result that the increased competency of the streams brought greater amounts of coarse debris onto the fan. The higher energy-level caused progradation and a consequent regressive relationship with the earlier sediments. The first pulse laid down an openwork gravel, and the next pulse, the sand matrix. Heavy minerals were brought in with the sand phase and not with the gravels. Thereafter, as the energy-level dropped, transgression took place, with the deposition of finer-grained material, until a state of equilibrium was reached and deposition came to a standstill. End-of-cycle winnowing by the waters of the streams and the lake produced a greater concentration of residual heavy minerals on the erosion surface. Incipient tectonic activity caused tilting of the erosion surface, thereby producing the unconformable relationships between successive cycles. On the tilted surface, degradation was enhanced, winnowing intensified, and lag concentration brought to an optimum. Continued tectonic adjustment culminated in the prograding sedimentation of the next cycle. The turbulent gravels broke up the depositional floor and incorporated the thin streaks of lag gold and uranium on the unconformity. Thus, these minerals could have been introduced into the gravels in two processes – pick-up from the footwall sediments and downward infiltration during the sand pulse that succeeded the laying down of the pebbles.

That is the 1974 model. It will no doubt undergo still many more refinements before gold mining comes to an end in the Witwatersrand Basin. There are no complete and final solutions to problems in geology.

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