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GOLD IN THE PROTEROZOIC SEDIMENTS OF SOUTH AFRICA : SYSTEMS, PARADIGMS, AND MODELS

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by

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ABSTRACT

The Republic of South Africa is a metal producer of the first rank. Gold is the most important of the metals, and, up to the end of 1971, U.S. $ 32 billion had been realized from its sale. This figure was equivalent to 80 per cent of the total value of all metals sold. The gold province is located on the Kaapvaal craton which is composed of Precambrian sedimentary-volcanic and granite-greenstone assemblages ranging in age from 1 750 to 3 500 million years. This craton forms the southern part of the Southern African Shield. No significant gold mineralization has yet been found beyond the boundaries of this shield. On the Kaapvaal craton, five Proterozoic sedimentary-volcanic basins lie on an Archean basement. The basins were formed under continental conditions, and, in only one, is there any evidence of a major marine transgression. The gold so far won from the Archean rocks constitutes only 1.77 per cent of the total, with 98.23 per cent coming from the Proterozoic sediments. No gold mineralization has been exploited in the volcanics of the basins. Three types of goldfields exist : those in tectonically and metamorphically reconstituted ultramafics and mafics of the Archean greenstone belts, such as the Barberton-type field in the Swaziland Sequence; those in fluvial fan-lacustrine-interface environments, such as the Witwatersrand-type fields in the Pongola, Witwatersrand, and Transvaal sequences; and those in delta-open sea-interface environments, such as the Transvaal-type fields in the Transvaal Sequence. The Proterozoic host-rocks of sedimentary gold deposits are conglomerates, quartzites, shales, silty dolomites, dolomitic argillites, and algal mats. A series of conceptual process-response models has been constructed to generalize on times, environments, and conditions most favourable to the concentration of gold in Proterozoic sediments. These models refer to source-area, transfer system, and depository of gold moved in solid state or in solution from greenstone belts into cratonic clastic and non-clastic sediments, and there concentrated by physical, chemical, and biological agencies. Various models depict aspects of tectonism, erosion, transportation, stratigraphy, sedimentology, mineralization, biological activity, and atmospheric evolution, which interacted to produce the most significant Proterozoic gold mineralization in the world. From the models, a number of generalized conclusions have been drawn which might act as guides to future exploration for further gold deposits in South Africa.

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CONTENTS

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GOLD IN THE PROTEROZOIC SEDIMENTS OF SOUTH AFRICA : SYSTEMS, PARADIGMS, AND MODELS

GOLD MINERALIZATION IN SOUTH AFRICA

South Africa's Place as a Mineral Producer

The Republic of South Africa covers an area of approximately 472 000 square miles. Up to the end of 1971, the total value of mineral production from all recorded mining activity was a little over U.S. $ 49 billion. The exploited value of the crust thus averaged $ 104 500 per square mile. The unit regional value of the United States of America up to the same year was $ 266 100 per square mile, of Canada $ 17 400 per square mile, and of Australia $ 8 700 per square mile. These figures show that South Africa ranks very high in the list of great mineral-producing countries of the world. If the total value of all minerals extracted from the crust is broken down according to three broad classifications, it can be seen that fuels have contributed $ 174 100 per square mile in the U.S., $ 7 000 per square mile in South Africa, $ 5 100 per square mile in Canada, and $ 2 500 per square mile in Australia. The value per square mile of non-metallics mined in the U.S. was $ 50 500, in South Africa $ 11 300, in Canada $ 4 500, and in Australia $ 1 000. In the case of metals, the order of importance shows a marked change. The value per square mile of metals recovered in South Africa was $ 86 200, in the U.S. $ 41 500, in Canada $ 7 800, and in Australia $ 5 200.

The importance of South Africa as a mineral producer clearly lies in the concentration of metals, and, of these metals, gold has been the most substantial contributor, by far. Up to the end of 1971, the total value of gold produced stood at more than $ 32 billion, so that the unit regional value of this precious metal was of the order of $ 69 100 per square mile, equivalent to 80 per cent of the unit regional value for all metals.

Of course, gold is not distributed equally throughout all segments of the crust in the sub-continent, neither in time nor in space. Except for a very minor proportion, indeed, all the gold so far mined has been found in Precambrian rocks, and, except for a slightly greater fraction, all the gold has come from the northeastern quadrant of South Africa.

Geological Eras and Mineral Production

The history of crustal development and of associated mineralization in South Africa can be fitted into a framework of six eras, each of progressively shorter duration with the passage of time. The Botswanian era extends from the present to 150 million years, the Outeniquian from 150 to 500 m.y., the Bolandian from 500 to 1 000 m.y., the Bushmanian from 1 000 to 1 750 m.y., the Kaapvaalian from 1 750 to 3 000 m.y., and the Barbertonian from 3 000 m.y. to the formation of the Earth. Rocks of the Precambrian eras (Barbertonian, Kaapvaalian, Bushmanian, and Bolandian) are exposed over a total area of 154 000 square miles. From the Precambrian formations, minerals and mineral aggregates to the value of $ 43 billion had been mined up to the end of 1971. The unit regional value of the exposed Precambrian was thus $ 279 700 per square mile. Of this Precambrian mineral wealth, 85 per cent had been extracted from sedimentary basins, 9 per cent from igneous complexes, and 6 per cent from metamorphic terranes.

The key words, then, in the distribution of mineral wealth in South Africa are gold, sediments, Precambrian, and northeastern part of the country.

Gold in Time and Space

The Southern African shield underlies the eastern part of Botswana, the northeastern segment of South Africa, and Rhodesia. It consists of two cratons - the Kaapvaal and the Rhodesian cratons - separated by the Limpopo high-grade metamorphic belt. Significant gold mineralization in Southern Africa is restricted to the two cratons, of which the Kaapvaal crustal fragment is by far the more important contributor. The transition from Archean-type to Proterozoic-type crustal development took place on the Kaapvaal craton at about 3 000 m.y., and on the Rhodesian craton at possibly 2 700 m.y. In Rhodesia, gold mineralization occurs only in the Archean granite-greenstone terrane, whereas, on the Kaapvaal craton, it is found in both the Archean formations and in the Proterozoic sedimentary-volcanic basins. The host-rocks to Archean gold deposits are predominantly ultramafic and mafic rocks, many of a cyclic volcanic origin, with intercalated pyroclastics and chemical sediments. Proterozoic gold ore occurs, for the greater part, in clastic and non-clastic sediments. The clastic sediments are both fine- and coarse-grained, but there is a distinct tendency for greater concentrations of gold to occur in, or near, conglomerate horizons. The more important non-clastic host-rocks are silty carbonates, transitional between fine-grained clastic sediments and chemical precipitates. The gold has been remobilized in both the Archean and the Proterozoic deposits. In the former case, considerable generation and emplacement of granite, during the terminal phases of the Archean, was the main agent of the remobilization which was more extensive than that developed in the Proterozoic. Reconstitution of gold ores in the sedimentary-volcanic basins was brought about by diagenesis and by subsequent volcanic activity. Gold mineralization in the Archean is primarily igneous in origin, in the Proterozoic primarily sedimentary in origin.

The total value of gold mined on the Kaapvaal craton up to the end of 1971 was $ 32 610 million, of which $ 568 million (1.77 per cent) came from Archean ores, and $ 32 042 million (98.23 per cent) from Proterozoic mineralization.

In the Archean, the period between 3 000 and 3 250 m.y. was marked by granitic activity with which little primary gold mineralization was associated. In the classic greenstone area of the Barberton Mountain Land, in the eastern Transvaal, the period between 3 250 and 3 500 m.y. saw the development of the Swaziland Sequence which consists of three major groups - the Onverwacht, at the base of the 25 000 metre-thick assemblage, the Fig Tree, and the Moodies, at the top of the sequence. The Lower Division of the Onverwacht Group is composed essentially of ultramafics and mafics, with some intercalated pyroclastics and cherts. The Upper Division has significantly lesser amounts of ultramafics, while felsic volcanics are present in addition to the basalts. Pyroclastics and chemical sediments are again present. The Fig Tree Group is constituted by greywackes, shales, cherts, and banded ironstones, while the Moodies Group contains conglomerates, quartzites, shales, jaspillites, and minor volcanics. The Onverwacht and Fig Tree members were deposited under deep-water marine conditions, whereas the Moodies sediments were laid down in a shallow-water, terrestrial environment.

The bulk of the primary gold mineralization appears to be strata-bound along two particular stratigraphic horizons - the contact between the Lower Onverwacht Group and the Upper Group, and the contact between the Upper Onverwacht Group and the Fig Tree Group. Long held to represent typical mesothermal and hypothermal hydrothermal mineralization generated by the intrusive granites of the 3 000 - 3 250 m.y. period, the gold is now considered to be a product of older volcanic activity in Onverwacht times. The most commonly associated ore minerals are pyrite, arsenopyrite, and stibnite, with smaller amounts of copper, nickel, and cobalt minerals.

Five sedimentary-volcanic basins of Proterozoic age are preserved on the Kaapvaal craton : the Pongola Sequence (3 000 - 2 750 m.y.), the Witwatersrand Sequence (2 750 - 2 500 m.y.), the Ventersdorp Sequence (2 500 - 2 250 m.y.), the Transvaal Sequence (2 250 - 2 000 m.y.), and the Waterberg Sequence (2 000 - 1 750 m.y.). It would appear that no younger Proterozoic basins were developed on the Kaapvaal craton, and that a very considerable hiatus marks the time between the Waterberg Sequence and the Paleozoic cover of the Karroo Sequence. Each of the basins had a somewhat similar stratigraphic sequence : volcanics at the base and at the top, and fine and coarse clastics in the middle. Banded iron formations are present in the Pongola, Witwatersrand, and Transvaal sequences, and substantial dolomite development also occurs in the last-mentioned. The characteristic colour of the Waterberg rocks is reddish-brown, whereas the strata of all four of the other Proterozoic sequences are various hues of grey, white, black, and bluish-green. The general order of thickness of these sequences is 10 000 - 15 000 metres. Ultramafic igneous rocks are absent from the Proterozoic basins, and the volcanics are dominantly basalt-andesite, with some felsic components.

The value of gold won up to the end of 1971 from the five Proterozoic basins on the Kaapvaal craton was :

Waterberg Sequence	:	nil
Transvaal Sequence	:	$ 484 million
Ventersdorp Sequence	:	nil
Witwatersrand Sequence	:	$ 31 557 million
Pongola Sequence	:	$ 1 million

In the Pongola rocks, the gold occurs in conglomerates and shales; in the Witwatersrand, in conglomerates, quartzites, shales, and algal mats; in the Transvaal, in conglomerates, shales, silty dolomites, and dolomites. The commonly associated ore minerals in the Pongola are pyrite; in the Witwatersrand, pyrite and uraninite; in the Transvaal, pyrite and chalcopyrite. Placer and hydrothermal origins have been advanced for the Witwatersrand ores and hydrothermal processes for the gold in the Pongola and Transvaal rocks. It is now held that all the gold in the three basins is sedimentary in origin, having been transported either as detrital particles to accumulate in the coarser clastics, or in cold solution to be precipitated by the carbonates and the biogenic materials.

On the Kaapvaal craton, gold disappears from the record at the end of the Transvaal times, and is not seen again, to any significant extent, in the remainder of the Proterozoic or in the Phanerozoic. Gold mineralization is thus confined to the Barbertonian era and the early and middle periods of the Kaapvaalian era. The same statement can be made for the whole of Southern Africa - gold is of no major economic importance in rocks younger than 2 000 m.y. This time-line also marks an important change in the general nature of ore deposits in the sub-continent. Prior to 2 000 m.y., siderophile mineralization was of much greater significance than deposits of chalcophile elements; subsequent to 2 000 m.y., the reverse is true.

SYSTEMS, PARADIGMS, AND MODELS

With gold mineralization as extensive as it is in the early Proterozoic and in the Archean of South Africa, it would appear that the styles of crustal development which evolved over a long period of time remained consistently favourable to the concentration of the precious metal. A system of emplacement and redistribution was operative between Archean and middle Proterozoic times, i.e. for 1 500 m.y. at least, which lends itself to certain generalized statements concerning origin, dispersal, and deposition of the gold. Were the occurrences of gold lesser in number, smaller in volume, more widely distributed in time and place, and located in a greater variety of environments, generalizations would not be possible. The construction of models is an integral part of generalization.

Onions (1959) defined a system as "a set or assemblage of things connected, associated, or interdependent, so as to form a complex unity". In order to generalize about a system - in this case the processes and responses of gold mineralization over 1 500 m.y. in the eastern segment of the Kaapvaal craton - it is necessary to decompose the complexity into a set of relatively simple patterns in which information is organized in a manner that permits understanding and prediction. Process-response models can be regarded as types of filters through which complexity might be transformed into apparent simplicity. Such models are heuristic devices that are useful in deducing a permissive environment for as-yet undiscovered ore deposits from an indicative environment in which the characteristics and controls of known mineralization have been established and analyzed.

Meadows *et al* (1972) stated that : "A model is simply an ordered set of assumptions about a complex system. It is an attempt to understand some aspect of the infinitely varied world by selecting from perceptions and past experience a set of general observations applicable to the problem in hand". Sufficient experience has been gained, over 100 years of exploration and mining, of gold mineralization in South Africa to allow the design of several models which contain both general observations and justifiable assumptions regarding the evolution of the system of processes and environments particularly favourable to the generation of gold deposits in sedimentary assemblages. Information about the system can be structured on four levels : regional, areal, local, and random. The fundamental feature of models, according to Hagget and Chorley (1967), is a highly selective attitude to information, with that on the local and random levels being eliminated, so that a model achieves an overview of the essential characteristics of a domain. Because of this selectivity, models are approximations of reality, bridging the observational and theoretical components of natural phenomena.

The hierarchy of generalization within a system is : (1) facts, (2) models, (3) paradigms (Hagget and Chorley, 1967). Paradigms have been defined as inter-related networks of concepts, on a sufficiently general level, which indicate the nature of the goals of the operation and of the conventional frameworks within which these are pursued. Paradigms can be regarded as large-scale models, not as specifically formulated, within which lower-rank models are set (Hagget and Chorley, 1967). The value of a paradigm lies in the fact that it permits the progressive evolution of an array of models within its general terms, which, themselves, remain essentially unchanged with time.

Conceptual process-response models of Proterozoic basins in South Africa were first employed by Pretorius (1965) in attempting to generalize on the overall pattern of cyclicity in the stratigraphic successions of the Kaapvaalian sequences. Conceptual models for the exploration for further gold mineralization in the Witwatersrand Basin were subsequently constructed by Pretorius (1966), these models conforming to Hagget's and Chorley's (1967) definition of devices describing the class of objects or events to be studied, the kinds of measurements to be made, and the properties or attributes of these measurements. The present paper is an outgrowth of these two earlier attempts at stratigraphic-sedimentological modelling, and is an expanded endeavour to emphasize the broad characteristics of a geological system into which gold entered at about 3 500 m.y. and from which it disappeared at about 2 000 m.y. The sedimentary gold deposits are integral parts of the rocks which contain them. To understand the nature of the mineralization, the complex formational history of the Proterozoic sediments has to be simplified through generalizations of the regional and areal variables which determined the optimum depositional milieu for the different types of gold deposits.

PARADIGMS OF SEDIMENTARY GOLD

The gold which has been found in the Pongola, Witwatersrand, and Transvaal sequences of the Kaapvaalian era is firmly believed to be of sedimentary origin. Although some of it has been considered to be epigenetic in origin, no substantial evidence has yet been produced pointing to an acceptable source of magmatic hydrothermal fluids. Perhaps, the most doubt can be attached to the sedimentary origin of the gold in the dolomites and silty non-clastics of the Transvaal Sequence, since many of the features of these deposits can be accommodated in a volcanic fumarolic model. However, the weight of the arguments leans well to the syngenetic, sedimentary side for all the Proterozoic gold mineralization in the basins on the Kaapvaal craton.

Under these circumstances, the paradigm (super-model) for such mineralization is that depicted in Figure 1. For the gold to accumulate in the sediments of a depository, it must have been transported to the depositional site from a source-area, whether this be an Archean greenstone terrane or an earlier Proterozoic sedimentary basin. This paradigm is the fundamental generalization of the genesis of a Proterozoic sedimentary gold deposit in South Africa.

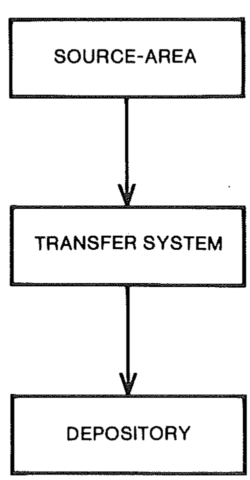

Figure 1 : *Paradigm of the components and environments necessary for the development of strata-bound, sedimentary gold mineralization in a Proterozoic basin in South Africa.*

The second paradigm is constructed in Figure 2. To activate the system shown in Figure 1, a series of energizers was necessary which produced a range of effects on successive operators. Igneous activity - essentially of an ultramafic-mafic nature, but with felsic magmatism also playing an important role - introduced gold and other metallic minerals into the Archean-type greenstone belts of the Barbertonian era. The gold, in the form in which it first entered the total system, was clearly of magmatic origin. Tectonic adjustment, consequent upon the cessation of igneous activity, uplifted the mineralized greenstones, thus making them vulnerable to processes of physical and chemical degradation, during which the incipient phases of the transfer system could procure the liberated gold from the source-rocks. Erosion placed the procured gold within the sphere of influence of the distributor component of the system, and fluvial transportation carried the products of erosion into a depository where they settled into a cyclic sequence of sediments. The overall energy within the system showed a progressive decrease from the time of tectonic uplift, which made the source-rocks available for erosion, to the time of laying down of the erosional debris in one of the Kaapvaalian yoked basins which developed on the South African shield.

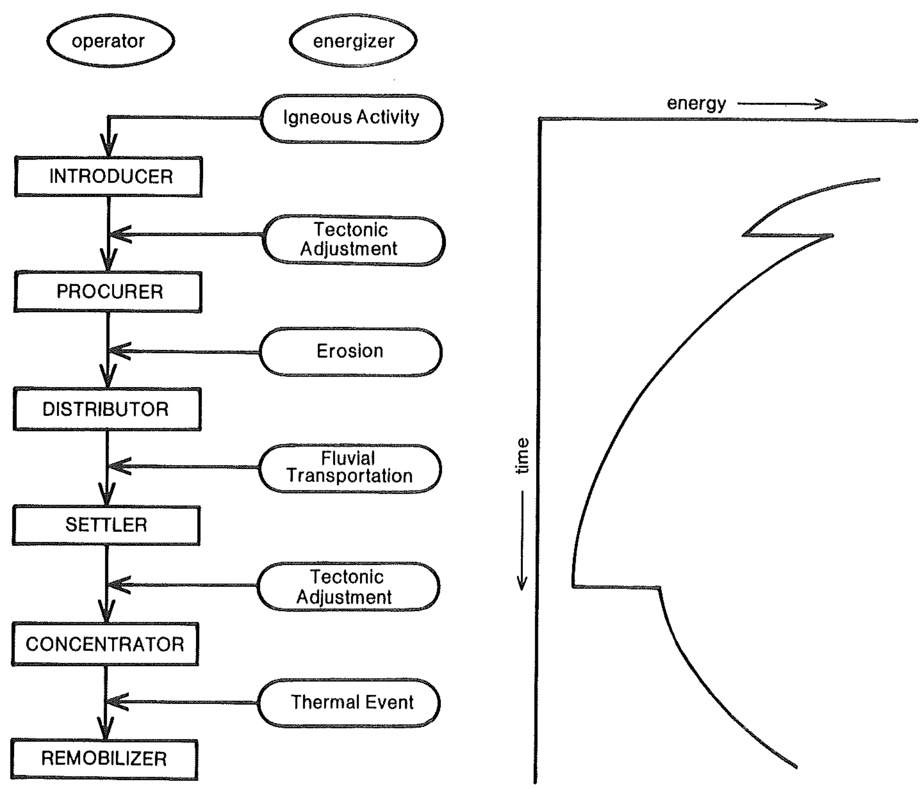

Figure 2 : Paradigm of the operators and their energizers that combine to produce a Proterozoic sedimentary goldfield in South Africa, and of the variations, in time, in the energy-level which prevails at different stages in the system.

The gold content of the first-stage sediments was too low to be of economic interest, and it was necessary to reconstitute the material in order to produce ore. For the physical reworking of the rocks, tectonic adjustment within the basin was necessary for uplift to recycle previously deposited material. Each cycle of reworking contributed to a progressively greater concentration of residual gold and other detrital heavy minerals. For the chemical reconstitution of the gold, an increase in the thermal gradient was required for mobilization of silica, gold, carbonate, and, to a lesser extent, other components of the sediments, and for the migration of these constituents to zones of lower temperature-pressure or greater chemical reactivity, where precipitation took place. To produce ore from the first-phase sedimentary protore, there was a progressive increase in energy as the basin underwent the tectonism and metamorphism which heralded the conditioning of the crust for the inception of the next basin in the Kaapvaalian sequence.

MODEL OF A SOURCE-AREA

The first stage in the Proterozoic gold mineralization system in South Africa was the introduction into higher crustal levels of Archean-type, mantle-derived igneous rocks ranging from ultramafic to felsic. Gold was preferentially contained in the ultramafic and mafic components. Siderophile metals were also more prevalent in these rock-types, while chalcophile metals showed a preference for the mafic-felsic members of the magmatic suite. Greater amounts of sulphur appeared to characterize the latter rock-types, so that sulphides, particularly pyrite, were present in higher concentrations as the igneous assemblage trended towards the felsic end-point. All these rock-types, together with later sediments, constituted the greenstone belts which were subsequently intruded by varieties of granite. The thermal gradient set up by these intrusions was the energizer which caused the remobilization of the gold in the more mafic rocks and the generation of hydrothermal deposits in the Barbertonian era.

Figure 3 is a model of the variations in mineralization in the source-area as a consequence of the changes in the relative volumes of ultramafic, mafic, and acid magmatic rock-types. Where ultramafics predominated, siderophile elements were dominant. Where felsics were present in much greater amounts, chalcophile elements characterized the types of associated mineralization. Where mafic and felsic rocks were approximately equal in proportion, both siderophile and chalcophile metals were in evidence. Gold, being siderophile, was more common in ultramafic and mafic rocks. Where the volume of felsic rocks was equal to, or greater than, the amount of mafic and ultramafic material, gold ceased to be present in any substantial quantities. As gold diminished, so pyrite and other sulphides assumed greater importance. From the model, it follows that the optimum Archean-type source-area for Proterozoic sedimentary gold was the one which contained the greater proportions of ultramafic and mafic rock-types.

The model also offers a possible explanation for the uniqueness of the Kaapvaal craton as a world-source of gold. In a very generalized manner, the relative proportions of ultramafic, mafic, and felsic material in greenstone belts have been used to characterize three of the major gold-producing Archean cratons in the world. The Kaapvaal craton of South Africa certainly shows a relative paucity of felsic rock-types and a minor amount of significant copper-lead-zinc mineralization. The opposite is true of the Superior craton of Canada, where chalcophile ore deposits are a characteristic feature of the Archean greenstone belts. The Yilgarn craton of Australia might be intermediate between the two types. Because the Yilgarn and Superior cratons had lesser volumes of ultramafics, they had lower potentials for providing the amounts of gold which were drawn from the Kaapvaal greenstone belts to feed into the Witwatersrand and other Proterozoic basins.

The variations in relative proportions of rock-types in the three cratons might also reflect an age difference for the greenstone belts in South Africa, Australia, and Canada. It has been stated earlier that the transition from Archean-type crustal evolution to Proterozoic-type took place in South Africa at about 3 000 m.y. and in Canada at about 2 500 m.y. In Australia, the transition was probably between these two dates. It is possible that, the earlier in Earth history a greenstone belt formed, the greater the proportion of its ultramafic constituents. The younger the greenstones, the more significant was the volume of felsic rock-types. If such was the case, then the source-areas most favourable to the subsequent generation of sedimentary gold deposits would have been those containing the oldest developments of Archean-type ultramafic-mafic greenstone crust.

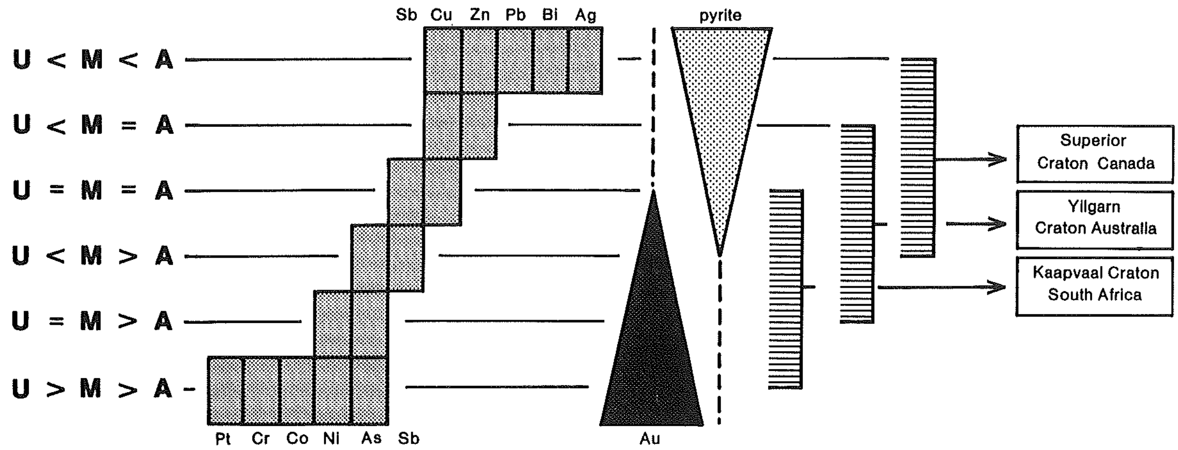

Figure 3 : *Conceptual model of the igneous rocks, ore metals, and amounts of gold and pyrite in a potential source-area for a Proterozoic goldfield. U : relative volume of ultramafic intrusives and extrusives in the igneous components of an Archean-type greenstone belt; M : relative volume of mafic igneous material; A : relative volume of acid igneous material.*

MODELS OF TRANSFER SYSTEMS

The evidence from all investigations points overwhelmingly to the fact that the erosional debris from the source-area was transferred to the depository through the medium of a fluvial system. The Kaapvaalian sedimentary basins were essentially intracratonic in nature, and formed under continental conditions, although extensive marine transgression is apparent in at least one instance. It has also been shown that differential subsidence of the depository and uplift of the source-area were brought about by tectonic adjustments which had their more important development along the margin of the basin.

A model of the transfer system which was operative into the Proterozoic basins of South Africa is portrayed in Figure 4. An essentially high-energy system was represented by the short linear fluvial agency, while the long, meandering fluvial processes were associated with a lower-energy regime. A Witwatersrand-type goldfield was the response to the former system, and a Transvaal-type goldfield to the latter. The first system prevailed where inter-montane, intracratonic sedimentary basins were formed, while the second characterized the period when the general topography of the crust was subdued and marine transgression developed. The high-energy regime would have its present-day analog in a basin-and-range-type of environment, except that far greater quantities of water would be available then is the case, say, in the western United States of America, and the low-energy situation in a continental shelf-type of environment.

The Witwatersrand-type transfer system was best represented during the period 2 500 - 2 750 m.y. The fluvial fans formed very close to the uplifted source-area which consisted essentially of Archean-type granite-greenstone terrane, and these fans constituted the interface

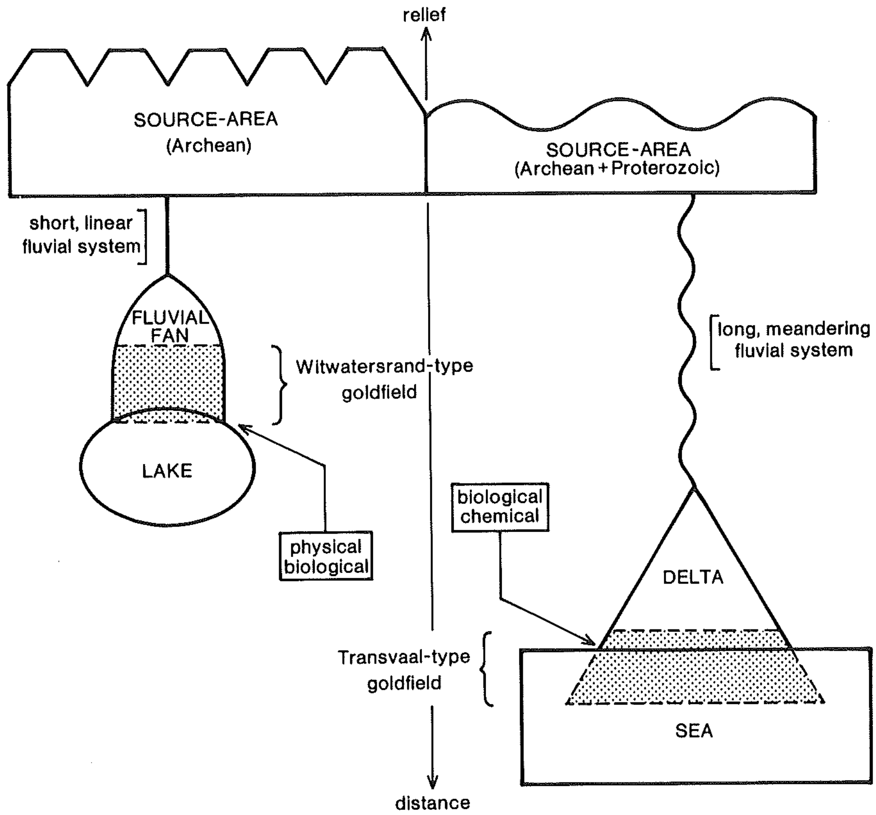

Figure 4 : *Conceptual model of the transfer systems which collect erosional debris, including gold in solid state and in solution, in the source-area, and transport it to a depository, where it is concentrated by physical and biological agencies to form a Witwatersrand-type goldfield in coarse clastics and algal mats, and by chemical and biological agencies to form a Transvaal-type goldfield in fine clastics and non-clastics.*

between the short, relatively linear river systems and the shallow-water lacustrine systems. The rivers debouched from canyons, flowed a comparatively small distance over a piedmont plain, and then dispersed, through a braided-stream pattern, into the depository. The gold was transported essentially as detrital particles, and, to a lesser extent, in solution which probably took the form of chloride- or cyanide-complexes. The fluvial fan-type goldfield was a basin-edge phenomenon, with the host-rocks comprising conglomerates, sands, silts, shales, and algal mats, the last-mentioned of which developed during periods of relative quiescence in the depositional environment. The concentration of the gold took place physically, through gravity-settling, and biologically, through interaction between the dissolved gold and the algal colonies.

The Transvaal-type transfer system was optimally operative during the period 2 000 - 2 250 m.y. More subdued relief in the source-area, marine transgression over the cratonic area, and a more gentle paleoslope, during the middle stages of the Transvaal Sequence, culminated in a long, meandering, fluvial system which developed a delta at some distance out into the basin. A Transvaal-type goldfield was thus not a basin-edge feature, but was formed on the distal side of the depositional axis. The source-area consisted of both Barbertonian granite-greenstone rock-types and previously deposited Proterozoic sediments and volcanics, belonging mainly to the Witwatersrand and Ventersdorp sequences. The gold was brought into the depository in solution, and chemically and biologically precipitated in the delta that formed the interface between the fluvial system and the marine environment. Estuarine conditions were probably the more suitable for the concentration of the gold.

The Witwatersrand-type transfer system operated during regressive conditions, and the Transvaal-type under transgressive conditions. Gold mineralization resulting from the former processes is present in the Pongola, Witwatersrand, and Transvaal basins, and has not been found, as yet, in the Ventersdorp and Waterberg sequences. In that the only major marine transgression in the Kaapvaalian era of South Africa took place during Transvaal times, the deltaic-type goldfield has so far been found only within the confines of the Transvaal basin. The models which have been constructed of the transfer systems require that gold was moved from the source-area to the depository by both physical and chemical means. Detrital particles were transported by traction or in suspension, together with the clastic components of the debris of the source-area. Gold in solution was apparently more abundant than in present-day surface waters. It is considered that the dissolved gold was in the form of chloride- or cyanide-complexes, which were more prevalent in the Archean and early Proterozoic periods because of the more primitive composition of the atmosphere, the generally anoxygenic environment, and the dominance of reducing conditions. With the evolution of a progressively more oxygenic environment, gold remained in solution for lesser periods of time and was transported over shorter distances.

MODELS OF DEPOSITORIES

Stratigraphic Models

The Proterozoic basins of the Kaapvaalian era are characterized by three common features : (i) the basin-fill began with a volcanic assemblage and ended with a volcanic assemblage, and had the major accumulation of sediments between the two periods of volcanic activity; (ii) the sedimentation was cyclic in nature; and (iii) the general lithological successions were repeated from one basin to another. Repetition and cyclicity were typical responses to the processes of basin development. These phenomena led to the attempts by Pretorius (1965) to view the stratigraphy of the Kaapvaalian basins in terms of harmonic patterns.

Basin formation in the early and middle Proterozoic, at least, of South Africa had a periodicity of about 250 million years (five basins between 1 750 and 3 000 m.y.). This systematic repetition might be regarded as the first harmonic. The next most conspicuous feature of the fill of each basin is the succession of volcanics-sediments-volcanics, which might be considered as a response to a third harmonic of cyclic repetition. Further cycles of sedimentation, of greater and smaller scales, which are numerous in each one of the basin sequences, can be viewed as patterned reflections of fifth, seventh, and still lower-order harmonics. Odd harmonics only are employed, to keep the processes in phase. Each harmonic was interacting with each lower-order harmonic, with the result that the summed response to all the cyclic processes was a gross pattern of superimposed harmonics into which the variations in stratigraphy and lithology could be fitted. It is possible that harmonic analysis could be applied satisfactorily only to basins which developed on a stable craton where the tectonic styles of basin subsidence and source-area uplift remained relatively constant over long periods of time. The Proterozoic basins of the Kaapvaal craton in South Africa certainly meet these requirements.

In Figure 5 is shown the resultant curve of superimposing in-phase first and third harmonics. On the left of the diagram, the primary harmonics are shown in broken lines, and the secondary harmonic, which is the product of the interaction of the two, is drawn in a solid line. The most obvious consequence of the superimposition is the conversion of the dromodarian primary harmonics into a bactrian secondary harmonic. On the right of the diagram, portions of the first and third harmonics and of the resultant superimposed effect are magnified. The point to be stressed in the superimposed harmonics is that, of the three inflexion points, the bottom and the top have the

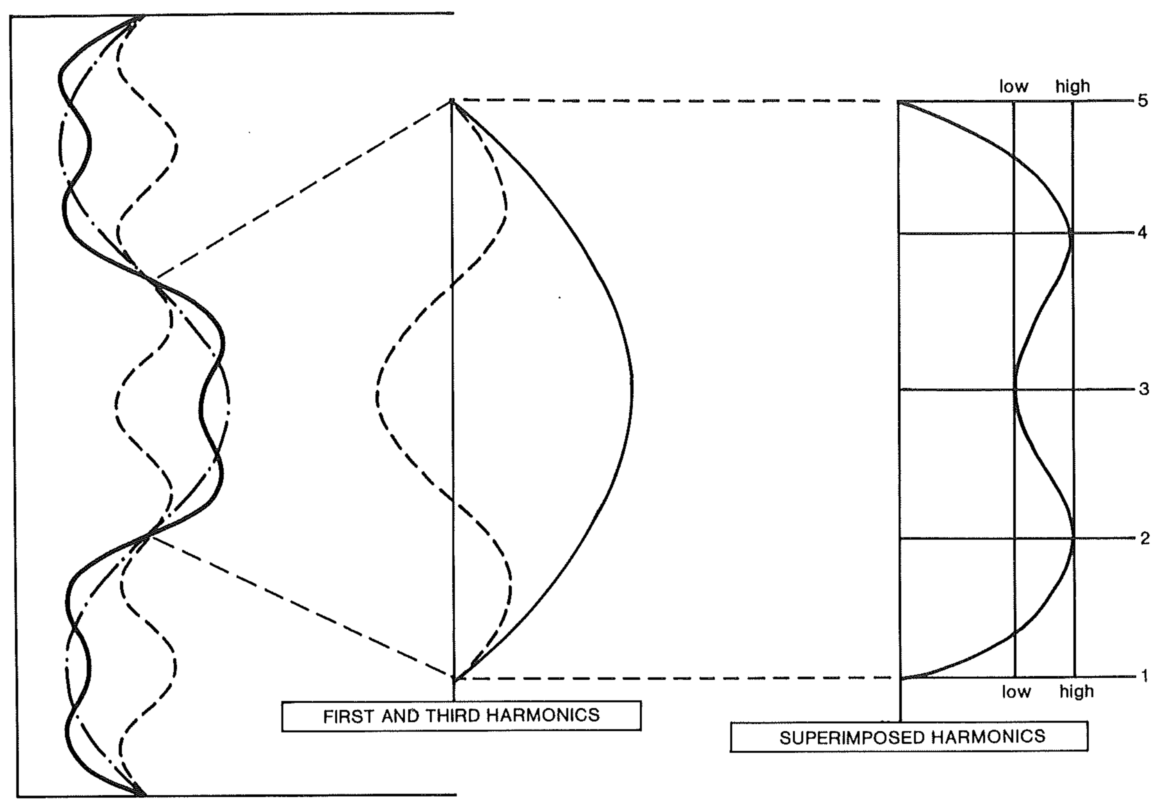

Figure 5 : Model of the pattern resulting from the superimposition of a third harmonic on an in-phase first harmonic. Dromodarian discrete curves are converted into bactrian superimposed curves.

higher amplitude, with a lower magnitude attached to the central point. Rates of change in the resultant curve are highest in segments 1-2 and 4-5, intermediate in segments 2-3 and 3-4, and lowest at the inflexion points 2, 3, and 4.

If the vertical axis of Figure 5 is made to represent time, and the horizontal axis energy, then the stratigraphic model of Figure 6 can be constructed, which depicts the sequence of lithologies that made up each of the Kaapvaalian Proterozoic sedimentary-volcanic basins. Energy has been scaled according to that prevailing in the depository when non-clastics, fine clastics, coarse clastics, and volcanics were being introduced, it being implied that more energy was required to bring igneous material up from depth and to extrude it into the basin than was needed to form chemical sediments. In Sequence X, Group A would be composed of coarse basal clastics and a substantial volume of volcanics; Group B of coarse clastics, fining upwards; Group C of non-clastics or fine clastics, depending on whether the base-level of energy was lower or higher; Group D of fine clastics, coarsening upwards, and presenting a succession somewhat similar to that of Group B; and Group E of terminal volcanics and some coarse sediments. If the energy-base shifted to the right, then the overall energy within the whole system would have been lower, and lesser volcanics and greater non-clastics would have appeared in the stratigraphy, as was the case with the Transvaal Sequence. If the energy-base was displaced to the left, then the depository would have formed under a generally higher energy-level, with the result that non-clastics would not have appeared in the stratigraphic assemblages and volcanics and coarse clastics would have become much more prominent, as in the Witwatersrand Basin.

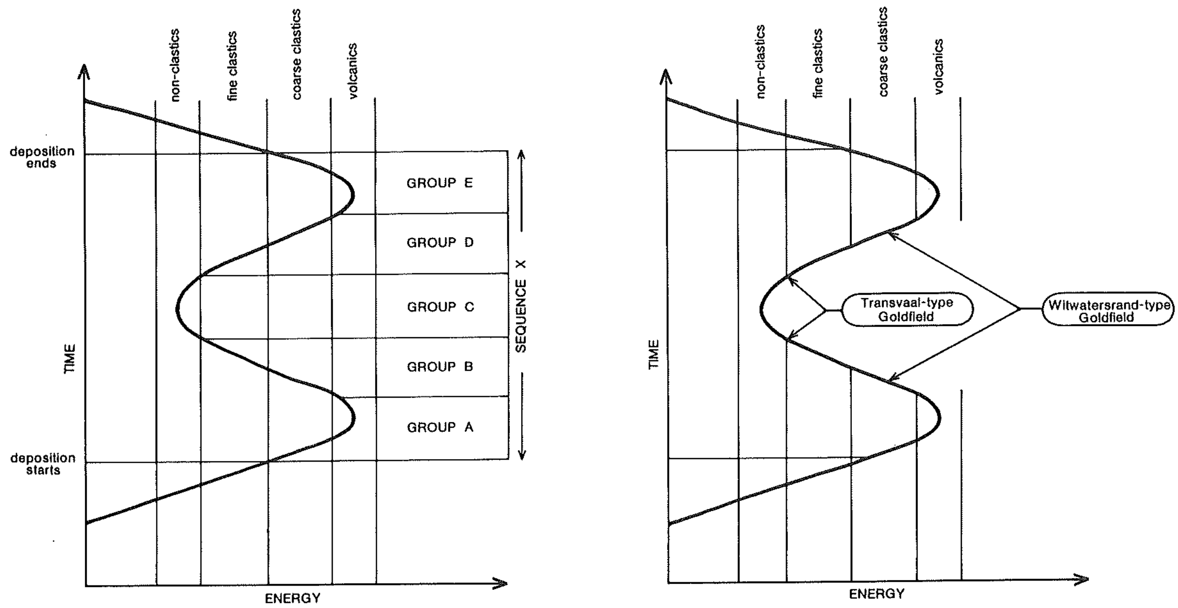

Figure 6 : *Conceptual model of the stratigraphic response to harmonic variations in the energy-level prevailing in a Proterozoic sedimentary-volcanic basin in South Africa. The first harmonic represents the periodicity of formation of successive basins, and the third harmonic the broad cyclic variations in lithologic response to changes in energy-level. The bactrian model curve requires a mirror-image repetition of the stratigraphic succession from the lower members of the depositional fill into the upper members. Maximum rates of change of energy-level occur during the intervals when Groups A and E are formed, and minimum rates of change at the three inflexion points. Intermediate energy-flux prevails during the development of Groups B and D. Because of the mirror-image phenomenon, ideally there are two optimum stratigraphic positions for the formation of an intermediate-energy, Witwatersrand-type goldfield, and two positions for a low-energy, Transvaal-type goldfield.*

In the Witwatersrand Sequence, Group A would be represented by the Dominion Group, Group B by the Hospital Hill-Government Group, Group C by the Jeppestown Group, Group D by the Main-Bird - Kimberley-Elsburg Group, and Group E by the Klipriviersberg Group. In the Transvaal Sequence, Group A would have its equivalent in the Lower Wolkberg Group, Group B in the Upper Wolkberg - Black Reef Group, Group C in the Malmani Group, Group D in the Pretoria Group, and Group E in the Rooiberg Group. The bactrian nature of the superimposed harmonics curve explains the fact that the lithologies of Groups A and B are repeated, in reverse, in Groups D and E, while the lithologies of Group C appear only once in the stratigraphic succession.

In the right side of Figure 6, the model shows where the various types of goldfields would be placed in the stratigraphic column. The Witwatersrand-type goldfield would occur in Group B or in Group D, in the lower part of the former, where coarse clastics would be more abundant than fine clastics, and in the upper part of the latter, where the same lithofacies would prevail. Some detrital gold would also occur in the coarse clastics of Groups A and E, but would be of much lesser economic significance, due, probably, to the fact that the rate of change of energy would be higher in the initial and terminal groups. Conditions would be too high-energy to favour the settling of large quantities of gold which, in the Proterozoic of South Africa, was always of a very small grain-size. Better conditions for physical concentration of gold would have occurred in the time intervals of intermediate energy-flux, associated with transgression in Group B and regression in Group D. In the Witwatersrand Basin, in particular, coarser clastics laid down under regressive conditions during a period of intermediate rate of energy-change were the optimum sites for the concentration of detrital gold. Group D would have a greater economic potential than Group B, because of the processes of regressive reworking which would characterize the former.

Transvaal-type goldfields would be distributed over a much smaller stratigraphic interval than Witwatersrand-type, because of the fact that Group C-type depositional environments would have developed only once in the broad stratigraphic history of a basin. The Transvaal-type goldfields would be preferentially located where Group B merged into Group C, via a transgressive relationship, and where Group C was transitional into Group D through the medium of a regression. This type of gold mineralization would be characteristic of an environment where the overall energy-level was low and where the rate of change of energy-level, with time, was slow.

In an ideal basin, containing gold-bearing sediments, auriferous horizons of very low economic potential would occur in the basal coarse clastics of Group A; of low potential in the coarse and fine clastics of Group B; of intermediate potential in the intercalated fine clastics and non-clastics of Group C; of high potential in the fine and coarse clastics of Group D; and of intermediate potential in the coarse terminal clastics of Group E. Needless to say, this ideal arrangement has not been found in any one of the Kaapvaalian basins. The Pongola Sequence has its low-rank gold mineralization in the equivalents of Groups B and C; the Witwatersrand Sequence its high-rank mineralization in Groups A, B, C, and D; and the Transvaal Sequence its intermediate-rank mineralization in Groups B, C, and D. No gold deposits of any importance have thus far been discovered in the Ventersdorp and Waterberg sequences.

Model of a Transvaal-type Goldfield

The host-rocks of Transvaal-type sedimentary gold deposits are dolomitic shales and silts and silty and argillaceous dolomites that were laid down in the distal facies of a deltaic environment, probably when estuarine conditions prevailed. The rock-types are mixtures of deltaic muds and silts and shallow-water shelf-carbonates. Algal activity was high episodically during the formation of the fine clastic-non-clastic assemblage of low-energy strata. The protore represented the most distally transported gold entering the depository.

The gold was brought into the basin in solution, from which it was precipitated either chemically or biologically. The precipitants were carbonate material, colloidal particles of clay, and algae, either separately or in combination. The gold in the protore of dolomitic silt was sub-microscopic in size, and the rock gave no readily visible sign of being a potential ore of gold. The protore was converted to ore by tectonic and thermal processes. In the former case, bedding-plane slip, associated with concentric-type folding of the strata, which characterizes the style of deformation of the Kaapvaalian basins, produced a pressure differential under which silica, gold, and some other metallic constituents migrated, to form conformably-disposed gold-quartz veins. The thermal energy for the redistribution of the gold into cross-cutting quartz veins was provided by the intrusion of large volumes of dykes and sills acting as feeders to the terminal volcanic stage of the succession. The exploitable gold was thus the product of lateral and vertical secretion of selected constituents of the original distal deltaic silts, muds, and carbonates.

No diagrammatic model has been constructed to illustrate the generalizations on the formation of a Transvaal-type goldfield. The main components have been depicted in Figures 4, 6, and 10, the last-mentioned of which will be discussed under the model of gold distribution through Kaapvaalian time.

Model of a Witwatersrand-type Goldfield

A Witwatersrand-type sedimentary goldfield is, in most of its general features, the antithesis of a Transvaal-type goldfield. It was the response to a high-energy environment on the edge of a regressing basin, and the host-rocks to the mineralization were essentially coarse clastics, although fine clastics also assumed considerable importance. Non-clastics found no place in the model of a Witwatersrand-type goldfield, and chemical precipitation of gold played a very minor role. The goldfields took the form of fluvial fans, or fan deltas, as opposed to the true deltas of the Transvaal-type goldfields, and developed relatively close to the source-area, so that the distance of fluvial transportation was comparatively short. Such goldfields were located on the proximal side of the depositional axis of a lacustrine environment.

Figure 7 is a generalized representation of the main elements of a typical Witwatersrand-type goldfield. The fluvial fan had its apex along a tectonically unstable basin-edge, where repeated uplift of the source-area side of the depository took place along longitudinal faults. Movement along such dislocations served two purposes : the fanhead section of an earlier fan was subjected to uplift and reworking into a later fan, and the midfan and fanbase sections were structurally depressed, ensuring optimum preservation. Downward displacement of the lower two-thirds of the fan also contributed to the transgression of the lake waters over the fan, during which winnowing of the sediments took place, resulting in the removal of the fines and the development of residual concentrations of heavy minerals as lag accumulations. Longshore currents in the lake moved the finer sediments farther from the entry point of the clastic material, and thus helped form the asymmetrical shape of the fans. The evidence to date suggests that the movement of water in the Proterozoic depositories on the Kaapvaal craton was in a clockwise direction for at least the greater part of the 1 250 m.y.-long history of basin development.

The fluvial fan was typically composed of two main lobes, each containing a greater concentration of braided stream channels, thicker accumulations of coarser sediments, including gravels, and high concentrations of gold and other heavy minerals. The angle between the two lobes was between 60 and 120 degrees, and the material between the lobes was of the same lower-energy character as the sands, silts, and muds which were deposited along the fan margins and the fanbase. In these same segments of the fan, conditions, on occasion, favoured the development of algal growths which took the form of thin, interwoven mats. In the channels on the lobes of the fan, detrital gold accumulated by gravity settling. For the small grain-size of the gold particles, the energy conditions in the fanhead section were too high to permit any substantial quantities of gold concentrating, with the result that this facies of the fan sediments normally had the lowest gold content. The highest amounts of gold were usually in the midfan section. In the fanbase section, the energy-level was too low to support the transportation of significant amounts of detrital gold beyond the midfan environment. However, gold in solution reacted with the algal material in the fanbase area, and the quantities of this absorbed gold often made the fanbase sediments hosts to important mineralization.

The build-up of a fan was accomplished in a series of pulses of sedimentation, which started with progradation during regression, proceeded through aggradation during transgression, and ended with degradation during stillstand. Such a combination of pulses constituted a cycle. Figure 8 has been constructed to portray the evolving pattern of sedimentation during the cyclic accumulation of coarse and fine material on a fluvial fan. A new cycle was initiated through tectonic adjustment along the longitudinal faults bounding the source-area. This adjustment produced a steepening of the gradient of the paleoslope, with the result that the increased competency of the fluvial system brought greater amounts of coarser debris onto the fan. The prevailing higher energy-level also caused the fan to prograde out into the depository, thus establishing a regressive relationship between the end-sediments of the previous cycle and the initial clastics of the new cycle. The coarser material took the form of an openwork gravel. The matrix, of sand-size, was introduced during the next pulse of regressive sedimentation. The sand infiltrated the gravels, so that there was a continuum between the matrix of the conglomerates and what became the hangingwall quartzites. Heavy minerals, including gold, were transported with the sand, and by gravity settling and subsequent jigging and winnowing, were concentrated between the pebbles. As the energy-level fell, finer and finer material was deposited on the fan, and transgressive conditions took over from the regressive environment which favoured the formation of a basal gravel at the beginning of the cycle. At the end of the cycle, no more clastics were introduced by the fluvial system, and sediment accumulation gave way to degradation. The amount of winnowing increased with time, with the consequent greater concentration of residual heavy minerals on the erosion surface. Incipient tectonic activity caused tilting of the surface, in which process originated the unconformable relationship between the two cycles of sedimentation. On this tilted surface, degradation was enhanced, winnowing was intensified, and lag concentrations of heavy minerals were brought to an optimum. The continued tectonic adjustment then culminated in the prograding sedimentation which marked the beginning of the next cycle. The gravels, washing in under somewhat turbulent conditions, broke up their depositional floor, in some instances, and incorporated into their bed the thin

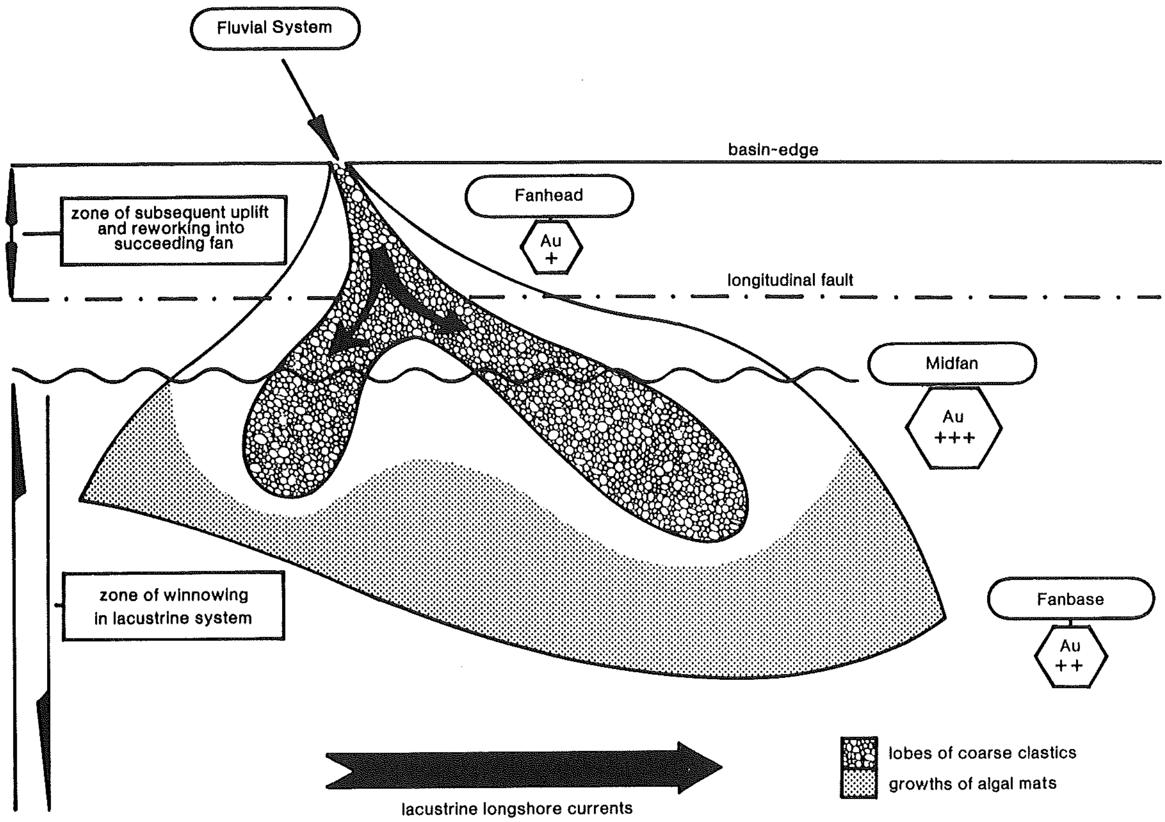

Figure 7 : *Conceptual model of a Witwatersrand-type goldfield. The fluvial system brings from the source-area unsorted erosional debris which undergoes sorting on the fluvial fan in accordance with a hydrodynamic regime radially decreasing in energy away from the apex of the fan. Because of the small grain-size of the gold particles, they are unable to settle, to any marked extent, in the fanhead facies. Optimum conditions for settling occur in the midfan facies. The energy-level becomes too low to move detrital particles in any quantity to the fanbase environment. However, gold in solution is precipitated by the algae which grow preferentially in the non-turbulent conditions along the margins and base of the fan.*

streaks of lag gold lying on the unconformity. Thus, the gold, under ideal circumstances, was introduced into the gravels in two processes - pick-up from the footwall sediments and downward infiltration from the sand pulse that succeeded the deposition of the pebbles.

The right side of Figure 8 models the variations in grain-size of sediment from cycle to cycle and in gold content in the basal and terminal phases of each cycle. Because tectonic uplift along the basin-edge caused erosion and reworking of the fanhead sections of previous cycles, relatively greater volumes of coarser material were deposited in successive cycles, so that, where tectonic activity was sufficiently intense, there was a general increase in grain-size stratigraphically upwards. This trend was also a response to the overall regressive nature of sedimentation in a shrinking basin. Since, in the model, each successively higher cycle represented

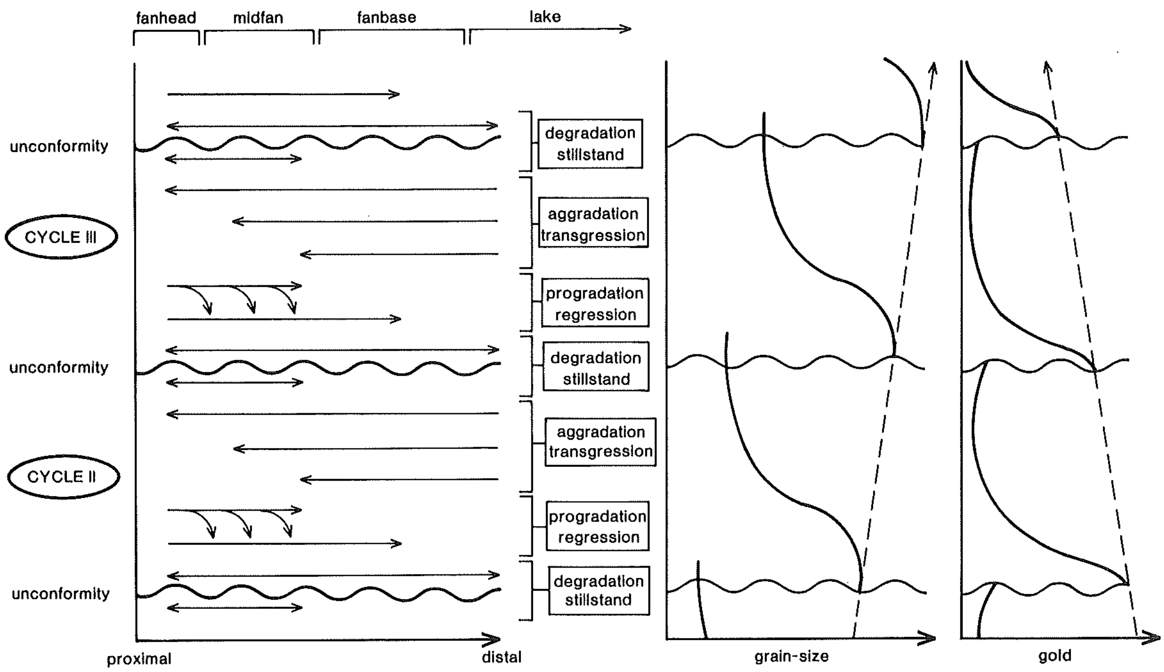

Figure 8 : *Conceptual model of the evolution of a depositional cycle on a fan, from progradation during regression consequent upon tectonic uplift along the basin-edge, through aggradation during transgression, to degradation during stillstand when the energy-level of the transporting currents is too low to bring erosional debris from the source-area onto the fan. Maximum winnowing by transgressive lake waters takes place during stillstand, to produce residual concentrations of lag gold. The second pulse of sedimentation during progradation brings in gold-bearing sand which infiltrates downwards into the openwork gravel of the higher-energy preceding pulse.*

a relatively more proximal facies than the underlying accumulation of sediments, there was a closer and closer approach to a fanhead facies stratigraphically upwards. As a result, the tenor of gold showed a generally diminishing trend from earlier to later cycles, because the energy-level in a fanhead section was usually too high to permit optimum conditions for the concentration of gold. The model also shows the distinctly enhanced intensity of the mineralization along the unconformity between cycles, both immediately below and immediately above the plane of discontinuity separating the cycles.

In that the Witwatersrand Basin is postulated to have been filled by the erosional debris from an Archean granite-greenstone terrane, it follows that the lithologies of the Witwatersrand Sequence should reflect the order in which the various formations of the greenstone belt were stripped off the source-area, entered the transfer system, and were brought into the depository. The best-known of the greenstone belts on the Kaapvaal craton is the Barberton Mountain Land, and the model devised for the development of this belt has been successfully used to interpret the stratigraphic successions and depositional histories of other greenstone belts of the Barbertonian era. The Swaziland Sequence of the Barberton Mountain Land is comprised of four groups of rocks, and each of these has three formations as constituent members. The Lower Onverwacht Group is dominated by ultramafic and mafic igneous rocks; the Upper Onverwacht Group has less ultramafic and more felsic components; the Fig Tree Group consists essentially of a turbidite assemblage of greywackes and argillites, with an important iron formation near the top; and the Moodies Group represents the first continental-type sediments, with quartzites and shales most prominent. The greater part of the gold mineralization is in strata-bound ore-bodies along the contacts between the Lower and Upper Onverwacht groups, and between the Upper Onverwacht and the Fig Tree groups.

The Witwatersrand Sequence consists of five groups of rocks : the Dominion Group at the base, in which mafic and acid volcanics are the major members; the Hospital Hill Group, of quartzites and shales, with a conspicuous iron formation in the upper sections; the Government Group, of quartzites and shales, mainly; the Jeppestown Group, of predominantly shales; the Main-Bird Group, of conglomerates, quartzites, and shales; the Kimberley-Elsburg Group, of conglomerates and quartzites; and the Klipriviersberg Group of mafic and acid volcanics and sediments. The Hospital Hill, Government, and Jeppestown groups are locally referred to as the Lower Division of the Witwatersrand Sequence, and the Main-Bird and Kimberley-Elsburg groups as the Upper Division.

The Witwatersrand Sequence formed in a yoked basin, with an active, fault-bounded margin along the northwestern rim of the depository, and a more passive, downwarping, southeastern edge. The main source-area lay to the northwest, and the Witwatersrand-type transfer system operated from northwest to southeast. The erosional remnants of Swaziland Sequence-rocks on the northwestern side of the basin are members of the Lower Onverwacht assemblage, and no rock-types of stratigraphically higher groups have been observed. On the southeastern side of the basin, the whole succession, up to and including the Moodies Group, has been preserved, in places, supporting the contention that the southeastern limits of the Witwatersrand depository suffered a far lesser degree of tectonic uplift than the northwestern, source-area region. Significantly, an attenuated stratigraphic column, consisting of lower-energy sediments, characterizes the southeastern side of the basin. More pronounced preservation of the Swaziland succession indicates that erosion did not reach down to the gold-bearing horizons at the bases of the Fig Tree and of the Upper Onverwacht groups, with the result that there are no significant Witwatersrand goldfields on the southeastern edge of the depository.

On the northwestern rim of the basin, the erosional level of the Swaziland Sequence lies below the gold-bearing horizons of the greenstone assemblage, and the Witwatersrand goldfields are all located along this edge of the depository. The Witwatersrand succession of this portion of the basin can be correlated with the stratigraphy of the Swaziland Sequence through the inverted stratigraphy model which is portrayed in Figure 9. The top-most members of the Swaziland Sequence contributed to material which formed the basal section of the Lower Witwatersrand Division. Since the Moodies Group contained quartzites, the recycling of these clastics produced the clean, arenaceous members of the Hospital Hill Group, which are the only true quartzites in the Witwatersrand succession. As the greywackes and argillites of the Fig Tree Group were stripped from the source-area, so were the sub-greywackes of the Government and Jeppestown groups formed. In the Upper Division, coarse clastic sediments were originally feldspathic quartzites, derived from the mafic and felsic volcanics of the Upper Onverwacht Group and from the ever-increasing volumes of granites that were eroded as more and more of the greenstone belt was stripped away. The lower members of the Swaziland Sequence thus constituted the source-material for the upper section of the Witwatersrand Sequence.

The iron formations of the Witwatersrand Sequence lie towards the top of the Hospital Hill Group, in the lower segment of the stratigraphic column. The iron formations in the Swaziland Sequence are located at the top of the Fig Tree Group, in the upper portion of the greenstone-belt column. They would have been the next source-rocks to have been eroded after the Moodies Group. The Moodies arenaceous strata went to form the Hospital Hill quartzites, while the Fig Tree iron formations, underlying the former, contributed to the development of the Hospital Hill iron horizons, above the latter. The major accumulation of shales in the stratigraphically higher Jeppestown Group points to a possible derivation from the argillites and greywackes of the Fig Tree Group, which underlie the iron formations.

The gold mineralization along the contact between the Fig Tree and the Upper Onverwacht groups was, by far, the more important of the two strata-bound sources of gold in the Swaziland Sequence. This mineralization was the first to be eroded, and was transferred to the sediments of

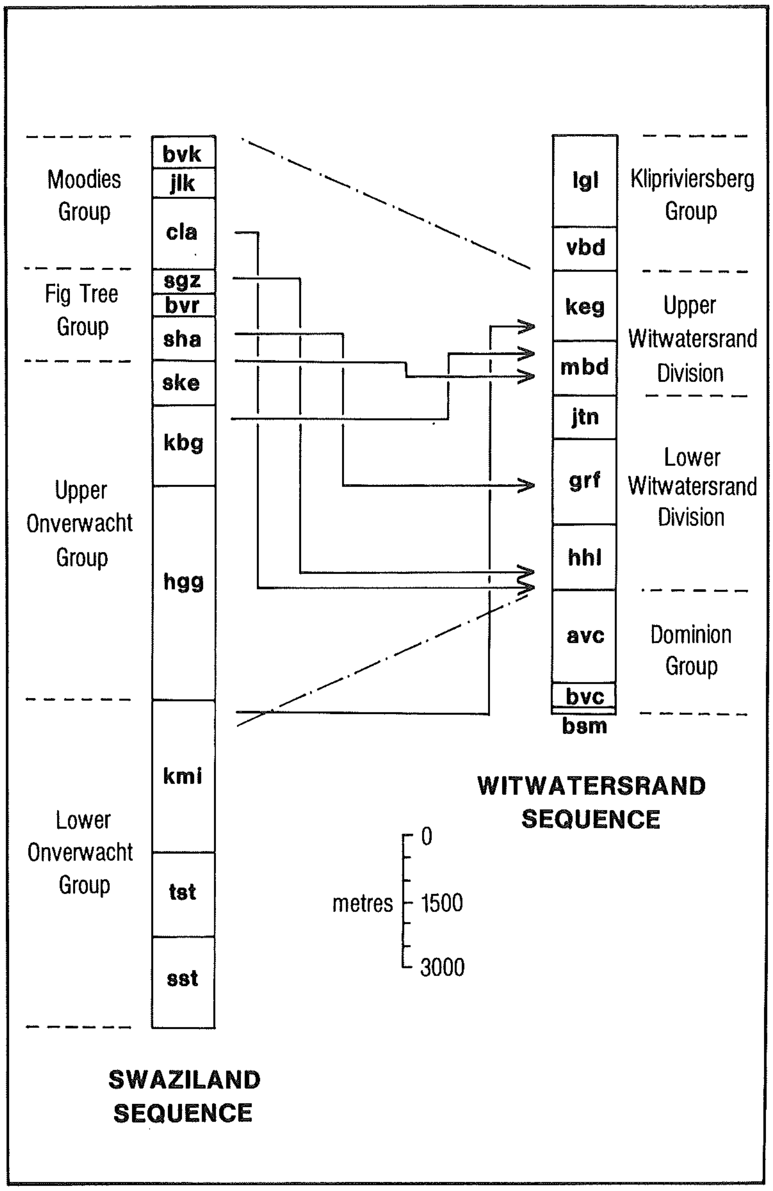

Figure 9 : An inverted stratigraphy model showing the influence of the later lithologies of the source-area on the early lithologies of the Witwatersrand Sequence, and vice-versa. Swaziland Sequence : bvk - Baviaanskop Formation; jlk - Joe's Luck Formation; cla - Clutha Formation; sgz - Schoongezicht Formation; bvr - Belvue Road Formation; sha - Sheba Formation; ske - Swartkoppies Formation; kbg - Kromberg Formation; hgg - Hooggenoeg Formation; kmi - Komati Formation; tst - Theespruit Formation; sst - Sandspruit Formation. Witwatersrand Sequence : lgl - Langgeleven Formation; vbd - Vaal Bend Formation; keg - Kimberley-Elsburg Group; mdb - Main-Bird Group; jtn - Jeppestown Group; grf - Government Group; hhl - Hospital Hill Group; avc - Acid Volcanic Formation; bvc - Basic Volcanic Formation; bsm - Basal Sedimentary Formation. The main gold-bearing horizons in the Swaziland Sequence are at the top of the Upper Onverwacht Group and the top of the Lower Onverwacht Group; in the Witwatersrand Sequence, in the Kimberley-Elsburg Group and the Main-Bird Group.

the Main-Bird Group, in which is located the major proportion of the Witwatersrand gold deposits. When the stratigraphically lower mineralization, along the contact between the Upper and Lower Onverwacht groups, was eroded and transported into the Witwatersrand Basin, it went into the auriferous beds of the Kimberley-Elsburg Group, which lie above the Main-Bird horizons and have a distinctly lower economic potential than the stratigraphically lower gold-bearing horizons.

MODELS OF GOLD IN TIME

Tectonic Elevation Model

The tectonics of the Precambrian crust on the Kaapvaal craton reflect a broad cyclical pattern of alternating higher and lower structural elevation with the passage of time, from the Barbertonian era to the end of the Kaapvaalian era. The Lower and Upper Onverwacht extrusive and intrusive rocks were probably emplaced under deep-water marine conditions. As emergence started to take place, the Fig Tree turbidites were formed in a somewhat shallower, but still deep-water, environment. The depositional floor rose above sea-level in Moodies times, so that the end of the Barbertonian era marked the transition from marine to continental conditions. Emergence continued, with the craton rising higher and higher above sea-level during Pongola, Witwatersrand, and Ventersdorp times. The rate of tectonic elevation was relatively slow. The continental land-mass probably stood at its highest during the period when the great volumes of Ventersdorp mafic and intermediate volcanics were sub-aerially extruded. Following this episode of significant igneous activity, there was a period of relatively rapid tectonic subsidence which culminated in the only extensive marine transgression during the evolution of the Kaapvaal craton. The Malmani shelf-carbonates of the Transvaal Sequence were the products of a time of minimum tectonic elevation. Emergence started during the middle of the Transvaal period, and continued to increase into Waterberg times. At the close of Waterberg deposition, Proterozoic sedimentary deposition ceased on the Kaapvaal craton, and moved to regions lying to the northwest, southwest, and southeast. The next sedimentation on the craton was in upper Paleozoic times.

Figure 10 depicts a model which has been constructed to show the variations in tectonic level with time, and the periods of essentially continental and mainly marine deposition. The time positions of the main stratigraphic horizons hosting gold mineralization have been indicated. Witwatersrand-type goldfields, which are best developed in the upper portion of the Witwatersrand Sequence and the lower section of the Transvaal Sequence, were preferentially formed when the craton was at near-maximum tectonic elevation. Under such conditions, the depositories took the form of inter-montane, yoked basins in which the fluvial fan-lacustrine environment was dominant. Transvaal-type goldfields, which are restricted to the middle portions of the Transvaal Sequence, originated when the craton was at near-minimum tectonic elevation during the Proterozoic. Marine transgression characterized such conditions, in which the delta-open sea environment was optimally developed.

Algal Activity Model

The oldest evidence of biological activity yet recorded has come from the Archean rocks of the Swaziland Sequence on the Kaapvaal craton. Bacteria and filamentous algae probably started developing about 3 300 m.y. ago, and went through cycles of evolution, which attained their acme during the marine transgression of the Transvaal period. The visible evidence of biological activity became more pronounced with time, as the size and frequency of the algal colonies increased. The first readily discernible remnants of algae are present in the Witwatersrand rocks. In the Swaziland Sequence, the evidence is on a microscopic scale, while no signs have as yet been noted of algal activity in the Pongola strata. Stromatolitic structures made their first appearance in the Ventersdorp sediments, and became most conspicuous in the Transvaal dolomites. The Waterberg Sequence has not yet produced any indications of algal activity. Empirically, it would appear that there might exist some degree of correlation between the presence of algal material in a sedimentary sequence and the presence of gold.

Figure 11 models the variations in the intensity of gold mineralization with time and in the apparent abundance of algae. It is not suggested that there is a one-to-one correlation, since the greatest amounts of gold, by far, were in the Witwatersrand Sequence, but algal activity was much more prolific in the Transvaal period. There was, nevertheless, a peak in algal development

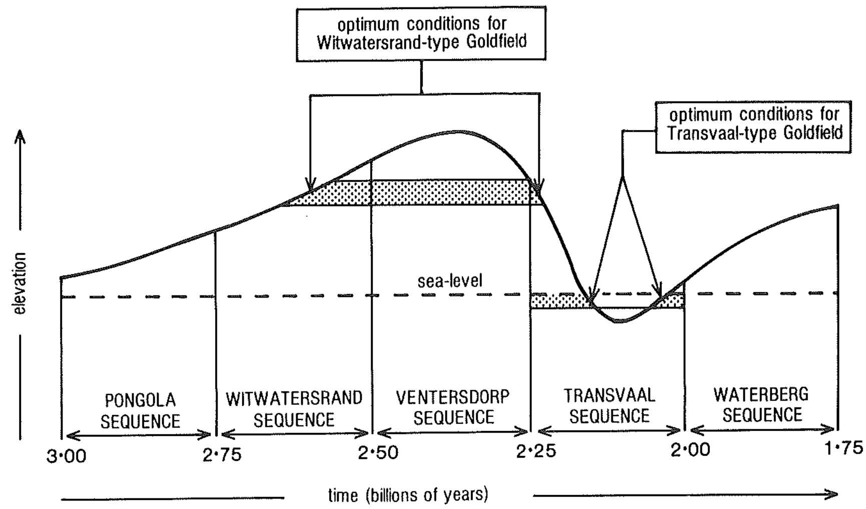

Figure 10 : *Conceptual model of the variation, with Proterozoic time, in the tectonic elevation above sea-level of the Kaapvaal Craton in South Africa. Conditions for the development of a Witwatersrand-type goldfield are at an optimum when the elevation is near, but not at, a maximum, and for a Transvaal-type goldfield when the elevation is near, but not at, a minimum.*

where there was a peak in degree of gold mineralization. The distribution of gold through the stratigraphic column shows that alternating sequences were impoverished and enriched in the amount of the metal present in the sediments. The Swaziland, Witwatersrand, and Transvaal strata acted as hosts to important ore deposits, while the Pongola, Ventersdorp, and Waterberg sequences were comparatively deficient in gold. The evidence, to date, of algal activity shows the same pattern. It might be concluded from the model that, where the environment favoured the development of algae, the physical-chemical-biological conditions were also such that gold settled out from traction or suspension, or was precipitated. This points to the river-depository interface as the optimum environment for the formation of stratiform gold mineralization in the evolution of the Proterozoic crust on the Kaapvaal craton in South Africa. Whether the interface was a fluvial-lacustrine product or a fluvial-open sea condition, it also favoured the maximum growth of algae.

The model shows two other features that record important environmental changes in the evolution of the sedimentary basins. The Pongola, Witwatersrand, Ventersdorp, and Transvaal sediments contain detrital sulphides, predominantly in the form of pyrite, but also as arsenopyrite and cobaltite. These particles are in hydraulic equilibrium with unequivocal detrital minerals that constitute the conglomerates and quartzites, and were transported, deposited, and preserved as sulphides. The abundance of these water-worn sulphide particles, plus the universal black, grey, blue, green, and white colours of the strata that compose the four sequences, point strongly to the fact that reducing conditions were prevalent at all times in the history of Proterozoic basin formation between 3 000 and 2 000 m.y. For such conditions to have been consistently present, it is likely that an anoxygenic atmosphere prevailed. This would help explain the apparent ease with which gold went into solution during the major part of the Kaapvaalian era, since chloride- and cyanide-complexes could have survived. Such solutions would have been short-lived where oxygen was freely available.

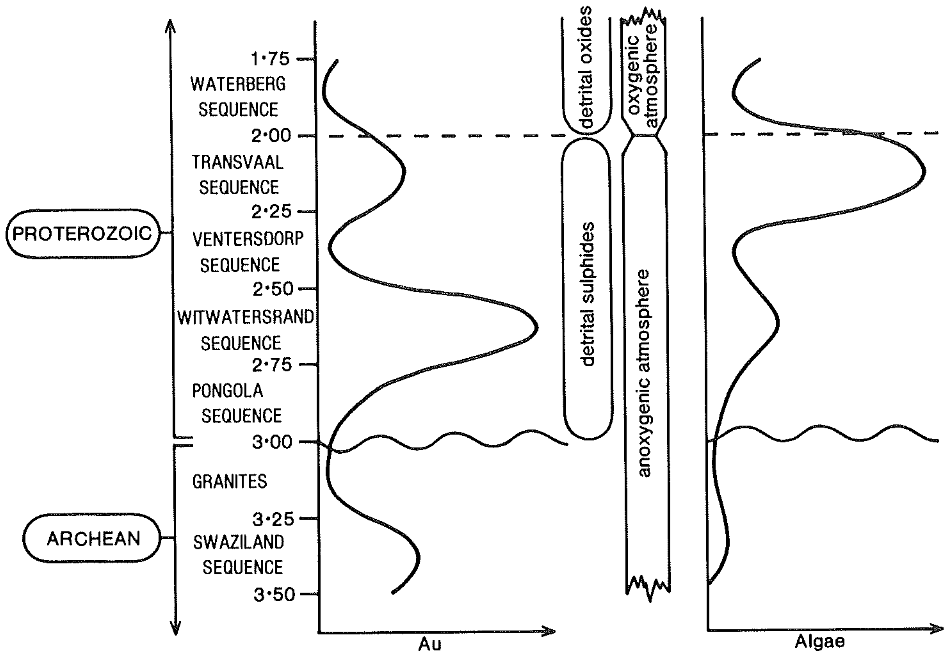

Figure 11 : Conceptual model of the variation, with Archean and Proterozoic time, in the degree of gold mineralization and in the intensity of algal activity. Alternating sequences show greater and lesser amounts of mineralization and of evidence of algal development. A significant change from an anoxygenic to an oxygenic atmosphere took place at 2 000 million years, following on the great bloom of algal activity during the middle Proterozoic. Detrital sulphides and sedimentary gold mineralization disappear from the South African stratigraphic column at this time, and detrital oxides and sedimentary copper-lead-zinc start appearing.

The first great bloom of Proterozoic algal activity took place at about 2 000 m.y. It probably contributed significantly, through photosynthesis, to increasing the amount of oxygen in the atmosphere. Thereafter, the detrital sulphides disappeared, and their place was taken by detrital oxides. Red beds were developed. Both of these features are well illustrated in the Waterberg Sequence. Exploration over the years has established that, at that time, sedimentary gold also disappeared from the stratigraphic record of South Africa. Major gold mineralization in sedimentary environments is thus restricted to the first cycle of continental emergence - the 1 250 million years between the end of Fig Tree times and the middle of Transvaal times. Subsequent cycles of emergence generated sediments in which copper, lead, zinc, and other chalcophile mineralization was developed, but not gold.

GROUND-RULES FOR GOLD PROSPECTING

The purpose of the models constructed has been to permit generalizations to be made about the distribution patterns in time and space of gold mineralization in the Proterozoic sediments of

South Africa. The use to which the models might be put is to allow predictions to be made as to the locations of maximum likelihood for further mineralization. Employing the models as predictive devices, the following conclusions have been drawn as guides to prospecting for new, permissive environments :

(1) Regions should be selected where the rocks are older than 2 000 m.y., no matter whether they belong to Proterozoic-type, sedimentary-volcanic, cratonic basins or to Archean-type, granite-greenstone terranes.

(2) Preference should be given to regions where the rocks were emplaced during the period of time when the primitive atmosphere was anoxygenic; hence, where the colours of the strata are blacks, greys, blues, greens, and whites; where red beds are absent; where detrital sulphides are present in the sediments; and where detrital iron oxides are absent (the parochial nature of the ground-rules can be seen in the fact that the important gold-bearing conglomerates of Ghana contain detrital iron oxides).

(3) Regions should be investigated where the preserved sediments were laid down during the first cycle of continental emergence after the formation of the Archean-type crust.

(4) In Archean-type strata, greater importance should be attached to the ultramafics and mafics which formed during the earlier stages of development of a greenstone belt, especially where such rocks show an extrusive origin, and where they have been reconstituted by metamorphic and tectonic processes; preference should be shown for the belts of greater age, which contain relatively larger volumes of ultramafic rocks, rather than for the younger greenstone belts which house comparatively more significant volumes of felsic volcanics.

(5) In Proterozoic basins,

(a) the geological periods should be selected when the tectonic elevation of the craton was near, but not at, its maximum, and when it was near, but not at, its minimum;

(b) the geological periods should be considered when algal activity was relatively more intense;

(c) the areas should be investigated where the greenstone belts in the source-area contained greater amounts of ultramafics, with the mafics, and lesser amounts of felsics, and where such greenstone belts have been eroded down to the lowermost members of the stratigraphic succession;

(d) the regions should be looked at where inter-montane, cratonic, yoked basins developed (for Witwatersrand-type goldfields), and where marine transgressions occurred over the cratonic edge (for Transvaal-type goldfields);

(e) the stratigraphic zones should be examined where intermediate ranges of energy-flux prevailed in the lower and upper halves of the stratigraphic record, and where minimal energy-flux occurred in the middle of the column;

(f) the areas on the proximal side, relative to source-area, of the depositional axis of the basin should be investigated for fluvial fan-lacustrine interfaces, and the areas on the distal side for delta-open sea interfaces; on the Kaapvaal craton, these areas would be on the northwestern and southeastern sides, respectively, with the fluvial fan-lacustrine environment possibly containing a Witwatersrand-type goldfield and the delta-open sea environment possibly a Transvaal-type goldfield;

(g) localities should be preferred where the fluvial fans show a regressive attitude upwards, indicating a shrinking basin with time and more favourable conditions of reworking of earlier fans into later fans;

(h) localities should be selected where midfan and fanbase facies are preserved;

(i) localities should be given a higher priority where unconformities are present in low-energy sediments which were laid down at the end of a depositional cycle; where conglomerates are developed above the unconformity; and where algal mats, not stromatolites, are preserved on the plane of unconformity; and

(j) localities should be investigated where silts and muds are interstratified with dirty carbonates; and where bedding-plane slip and dyke intrusion are well developed in such silty dolomites and dolomitic argillites.

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