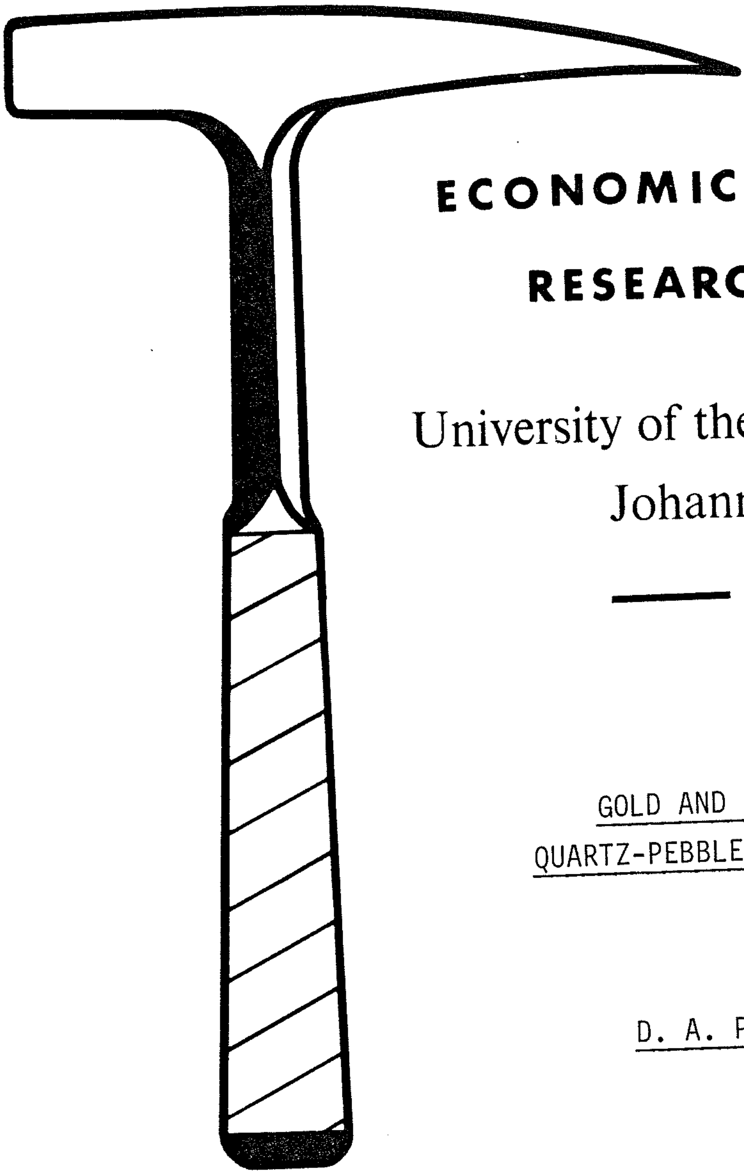

ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
Johannesburg

GOLD AND URANIUM IN QUARTZ-PEBBLE CONGLOMERATES

D. A. PRETORIUS

INFORMATION CIRCULAR No. 151

UNIVERSITY OF THE WITWATERSRAND
JOHANNESBURG

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by

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January, 1981

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ABSTRACT

The most important source of gold in the World is in conglomerates of Lower Proterozoic age, and production of uranium from this type of host-rock also has been substantial. The largest known reserves of both these ores are contained in quartz-pebble conglomerates and associated coarse-grained arenites. Pyrite is an important by-product, while platinum-group metals, thorium, and silver have also been recovered. Mineralized conglomerates have been discovered in many formations on every continent, but only four regions have sustained persistent mining operations : Witwatersrand in South Africa, Blind River-Elliot Lake in Canada, Tarkwa in Ghana, and Jacobina in Brazil. The most significant of these, by far, is the Witwatersrand Basin, knowledge of which has provided the basis for understanding the processes of ore-formation which are common to all the deposits.

The lower age-limit for the development of mineralized conglomerates is 3100 m.y. and the upper limit 1900 m.y. Rudites in typical Archean greenstone assemblages have not been exploited and Upper Proterozoic conglomerates (700-1600 m.y.) are conspicuously devoid of conglomerate-hosted ore-deposits. The development of Middle Proterozoic iron-formations and redbeds (1600-2200 m.y.) terminated the metallogenic epochs in which the auriferous and uraniferous conglomerates were formed. The strata which contain the rudites are preserved on the flanks of stable blocks of elevated Archean basement. Greater uplift of the more central parts of such blocks caused the Lower Proterozoic formations immediately above the basement to be stripped away, while the relatively negative regions surrounding the blocks have preserved the Upper Proterozoic and Phanerozoic cover.

The original basins containing the conglomerates were large in extent, at least 600 km long x 250 km wide, and were formed in an intracratonic or continental-shelf environment. Up to 15 000 metres of sediments and volcanics were laid down. Fluvial, deltaic, neritic, and shallow-marine sediments are characteristic, and deepwater turbidites and extensive chemical sediments are absent. The conglomerates are the products of a fluvial system in which low-sinuosity, high-energy, shallow-depth braided streams were operative. Gravels and sands, the latter carrying heavy minerals, accumulated either in paleovalleys on the erosion surface of the Archean basement or on fluvial fans or fan-deltas which developed where major river systems debouched into a large lake or inland sea. The structural fabric of the region played a critical role in the style and facies of sedimentation. The geomorphology of the basement reflected a pattern of superimposed interference folding and associated faulting, and the structural domes formed in such a pattern constrained the siting of the fluvial fans. Repeated diapiric-like uplift of the domes and of the sets of anticlines on which they are situated led to tilting and increased gradients of the depositional paleoslope, erosion surfaces on unconformities, and rim-faulting round the peripheries of the domes and along the limbs of the anticlines. All of these contributed to the processes of reworking and winnowing of the sands and gravels, which were essential to the concentration of the heavy minerals. Reworking was further enhanced where transgression of the depository waters up the fluvial fans resulted in reconstitution, by wave-action, of the sediments on the surface of the fan. Very fine-grained gold and uraninite which moved beyond the midfan area, where mineralized braided-stream channel conglomerates are at an optimum, were trapped, in rare instances, by algal mats which grew below wave-base in the low-energy fanbase environment. The unconformity is the site of maximum concentration of heavy minerals, whether these be in residual lag-gravels, winnowed sands, or algal mats.

Most of the conglomerates occur as basal components, or within the lowermost portion, of the stratigraphic succession. Such deposits conform more to the paleovalley-fill-type of sedimentation which appears to have a lower economic potential than fluvial-fan-type assemblages. Uranium is generally more prevalent than gold in the basal conglomerates. Fans develop higher in the sedimentary pile, and the most significant mineralization has been found in the upper half of a complete stratigraphic succession. Where the later part of the basin history is characterized by a depository shrinking in size and by generally regressive conditions, factors are at an optimum for the progressive reworking of material and the generation of high-grade concentrations of gold and uranium in coarse clastic sediments.

Extensive sedimentological, mineralogical, and geochemical studies in the past 25 years have produced evidence that very strongly supports a placer origin for the mineralization in the Lower Proterozoic conglomerates and sands. Remobilization of gold and uranium and reconstitution of the latter have been effected by diagenesis and metamorphism. The intimate relationship between sedimentary features, many tectonically controlled, and the sites of maximum concentration of heavy minerals points to a syngenetic origin for the mineralization. The source of the detrital minerals is, in all cases, indicated to be the Archean granite-greenstone basement terrane on which the sedimentary basins rest. The gold and pyrite were derived from volcanogenic mineralization in the greenstones. The uranium was contributed by a paleosol which formed in a regolith over younger, potash- and silica-rich granitoids belonging to the granitic component of the Archean assemblage. The degree of tectonic uplift of the provenance-area and the consequent level of erosion determined the relative proportions in the mix of granite and greenstone debris and, therefore, the prevalence of uranium or gold, respectively, in the conglomerates and sands of such Lower Proterozoic basins as the Jacobina, Tarkwaian, Huronian, Pongola, Transvaal, and Witwatersrand.

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GOLD AND URANIUM IN QUARTZ-PEBBLE CONGLOMERATES

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Published by the Economic Geology Research Unit
University of the Witwatersrand
1 Jan Smuts Avenue
Johannesburg 2001

ISBN 0 85494 646 2

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INTRODUCTION

Possibly, the very first ore-bodies that man worked for the recovery of metals took the form of stream and river gravels hosting concentrations of alluvial gold. Many centuries were to pass before it was recognized that similar ore-bodies occurred in well-consolidated, ancient rocks and that fluvial and other gravels, throughout the stratigraphic record, are potential exploration targets for a select group of metals and minerals. Records show that gold was won from very small-scale and primitive mining of Precambrian conglomerates along the Serra da Jacobina, in Bahia Province of northeastern Brazil, as far back as 1745. Auriferous conglomerates were identified in 1878 at Tarkwa in what was then the Gold Coast of West Africa, but it was the discovery, in March of 1886, of the gold-bearing banket of the Witwatersrand in the then South African Republic that brought world-wide recognition of the importance of conglomerates as major ore-bodies. Despite intensive prospecting for similar sediments in all parts of the world, it was not until 1953 that another discovery of first-rank economic status was made in the Blind River area of Ontario, Canada. Between 1886 and 1953 and since the latter year, indications of mineralization have been encountered in a very large number of conglomeratic assemblages of various ages, but economically-exploitable deposits of major importance have not been revealed outside of the known fields in South Africa, Canada, Ghana, and Brazil.

Gold and uranium are the only two elements that form primary ore-bodies in ancient gravels. By-products have included silver, platinum-group metals, pyrite, thorium, and diamonds. A speculative estimate points to conglomerates' having contributed about 50 percent of the total amount of gold that Man has won from the Earth in the past 5 000 years. By far the largest proportion has come from the Witwatersrand mines in South Africa, which, together, represent one of the greatest mineral provinces yet found. Conglomerates also provide a substantial percentage of the World's uranium production. Reserves of both gold and uranium in such host-rocks are impressively large. From the total worth of commodities won from ancient gravels, in relation to the gross value of the World's mineral production, it is apparent that conglomerates have earned an enviable reputation as sources of wealth.

As a measure of the importance of conglomeratic ore-bodies, the scale of mining in South Africa and Canada serves as a convincing indicator. Between 1886 and the end of 1979, approximately 35 500 metric tons (1,137 billion ounces) of gold were won from the Witwatersrand conglomerates and associated strata. The ore milled to yield this gold amounted to 3,585 billion metric tons. At various times, a total of 155 mines have been operative. Between 1952 and 1979, a little more than 100 000 metric tons of uranium oxide were also recovered from the treatment of 400 million metric tons of ore drawn from 34 mines. Mining is presently taking place at depths of up to 3 500 metres below surface. In the Blind River-Elliot Lake-Agnew Lake region of Canada, the exploitation of conglomerates, between 1955 and 1979, produced 90 000 metric tons of uranium oxide from the milling of approximately 90 million metric tons of ore. Thirteen mines have been worked at different times.

Incomplete records prevent estimates being made of the amount of gold recovered from conglomerates in Ghana and Brazil, but the figures must be very small in comparison to those quoted for gold-mining in the Witwatersrand Basin. Minimum production for the Tarkwa Goldfield might be 250 metric tons (8 million ounces) and for the Jacobina Goldfield 25 metric tons (805 000 ounces). Even smaller amounts of gold have been recovered from conglomerates in the Pilbara Block of Western Australia. There are no records of production from the very low-grade auriferous and uraniferous conglomerates which have been discovered in countries other than South Africa, Canada, Ghana, Brazil, and Australia.

AURIFEROUS AND URANIFEROUS CONGLOMERATES IN TIME

Conglomerates are a frequently-developed component of the sedimentary assemblages which have accumulated from Archean times to the Quarternary, but, volumetrically, they are of far less significance than other lithologies, such as sandstones, shales, and carbonate rocks. The number of rudites which show signs of mineralization is a fraction only of the total aggregate of conglomerates through the overall stratigraphic column, and the percentage which are mineralized to the extent of being economically exploitable is small to the point of being almost negligible. However, a few of these latter ore-bodies can be classified as among the most important sources of gold and uranium yet discovered. On very, very rare occasions, during a particular period of geological time, the bedecking of the Earth's crust with a sedimentary cover witnessed the laying down of quite anomalous concentrations of gold and uranium when depositional conditions favoured the formation of conglomerates.

The more extensive conglomerates, with higher-than-normal amounts of gold and uranium, which have been discovered, mainly on surface, and investigated are listed in Table 1. The main sources of this information are : Roscoe (1968), Smirnov (1969), Robertson (1974), Boyle (1979), and Houston and Karlstrom (1979). Of the 29 formations or groups of sediments, 11 (38 percent) have been economically exploited, but only 7 (14 percent) have provided ore for large-scale and long-term mining operations : the Banket Group (Tarkwaian) of Ghana, the Black Reef Formation (Transvaal) of South Africa, the Matinenda Formation (Huronian) of Canada, and the Turffontein, Johannesburg, Jeppestown, and Renosterspruit Formations (Witwatersrand) of South Africa. Relatively small-scale exploitation, for short periods, at sporadic intervals, has been undertaken on the Jacobina Group of Brazil, the Fortescue Group (Mount Bruce) of Australia, the Mozaan Group (Pongola) of South Africa, and the Uitkyk Group (Pietersburg) of South Africa.

The table clearly shows the concentration of mineralized conglomerates in the Lower Proterozoic, a feature which has been commented on by Roscoe (1973) and Robertson (1974). In addition to the first- and second-rank mineralized conglomerates in Table 1, other Lower Proterozoic rudites which have been reported to contain signs of very minor amounts of gold and uranium include : the Pitangui Formation, northwest of Belo Horizonte, Brazil (Robertson, 1974); the Mounana Formation, Gabon; the Dongargah Sequence, in Madhya Pradesh, India (Boyle, 1974); strata in southern Sayan, at Enissey Ridge, at Voronez, west of Lake Baikal, in the Vitom-Patom Highlands,

TABLE 1. Ages of Known Auriferous and/or Uraniferous Conglomerates

m.y.	Host-Assemblage to Mineralized Conglomerates			Region	Country
	Formation	Group	Supergroup		
700 to 1600	No recorded development of auriferous and/or uraniferous conglomerates				World-wide
1900	* ?	Banket	Tarkwaian	Tarkwa	Ghana
1900 to 2200	Period of Early-Middle Proterozoic Iron Formation				World-wide
2200	? Padlei Papaskwasati Indicator Moeda * Black Reef	Chitradurga Hurwitz Otish Otish Caraca Malmani	Dharwar ? ? ? Minas Transvaal	Mysore Northwest Territories Quebec Quebec Minas Gerais Transvaal	India Canada Canada Canada Brazil South Africa
2300	? ? Mississagi * Serro do Corrego Green Hole	Bababudan Montgomery Lake Hough Lake Jacobina Fortescue	Dharwar ? Huronian ? Mount Bruce	Mysore Northwest Territories Ontario Bahia Pilbara	India Canada Canada Brazil Australia
2400	Kainuu ? Magnolia Estes * Matinenda * Beatons Creek	Jatulian Segozero Deep Lake ? Elliot Lake Fortescue	Karelian Karelian ? ? Huronian Mount Bruce	Oulu Karelia Wyoming South Dakota Ontario Pilbara	Finland U.S.S.R. U.S.A. U.S.A. Canada Australia
2500	? ? ? Jack Creek * Turffontein	Tunguda Krivoy Rog Kursk Phantom Lake Central Rand	Karelian Karelian Karelian ? Witwatersrand	Karelia Ukraine Kursk Wyoming Transvaal Orange Free State	U.S.S.R. U.S.S.R. U.S.S.R. U.S.A. South Africa South Africa
2600	Sakami Lake * Johannesburg	? Central Rand	? Witwatersrand	Quebec Transvaal Orange Free State	Canada South Africa South Africa
2700	* Jeppestown	West Rand	Witwatersrand	Transvaal	South Africa
2800	* Renosterspruit	Dominion	Witwatersrand	Transvaal	South Africa
3000	* Denny Dalton	Mozaan	Pongola	Natal	South Africa
3100	* Mount Robert	Uitkyk	Pietersburg	Transvaal	South Africa

* Conglomerates which have been economically exploited

and in the Anabar-Olenek region of Siberia, all in the U.S.S.R. (Smirnov, 1969). Showings of uranium and gold have also been reported in Archean conglomerates of the Eldorado Formation, in the Sinoia area of Zimbabwe (Boyle, 1979), and of the Moodies Group, in the Barberton Mountain Land of South Africa (Saager, 1981). Because of the problematic age of the boundary between the Archean and the Lower Proterozoic, it is possible that the Sakami Lake conglomerates of Quebec, Canada, also might be of Archean age (Robertson, 1974). The Uitkyk Group, in South Africa, which is listed as the oldest of the Proterozoic hosts for mineralized conglomerates, could be of Archean age, and, like the Moodies Group, represent the terminal sedimentary phase of Archean-style greenstone development.

A well-preserved succession of Proterozoic basins in South Africa and confirmatory age-dating of the transition from Archean- to Proterozoic-style crustal development have permitted a classification of the Proterozoic period into three subdivisions : the Lower Proterozoic (2200-3100 m.y.), the Middle Proterozoic (1600-2200 m.y.), and the Upper Proterozoic (700-1600 m.y.). The important conglomerates of Canada, South Africa, and Brazil all belong to the Lower Proterozoic, while those of Ghana occur in the Middle Proterozoic. All lesser mineralized rudites, in all other countries in the World, are present in rocks of Lower Proterozoic age. The Middle Proterozoic is the period of world-wide iron-formation, prime examples of which are the deposits of the Lake Superior Region in the U.S.A., of the Quadrilatero Ferrifero in Brazil, of the Transvaal and northern Cape Provinces of South Africa, and of the Hamersley Range of Australia. Substantial deposition of carbonate rocks, with abundant algal stromatolitic development, also took place in the Middle Proterozoic. Atmospheric conditions changed during this period from anoxygenic (reducing), characteristic of the Lower Proterozoic, to oxygenic (oxidizing), typical of the Upper Proterozoic.

Uranium mineralization in conglomerates, in which detrital uraninite played an important role, did not continue beyond the end of the Lower Proterozoic and the terminal phases of anoxygenic conditions. At the same time, detrital pyrite, which is, by far, the most abundant heavy mineral in the conglomerates, ceased to be a characteristic component. The Middle Proterozoic conglomerates of Ghana contain only gold, and no uranium, and the common heavy mineral is detrital hematite, not pyrite. Gold mineralization, thus, did continue into the Middle Proterozoic, but, in the Upper Proterozoic, both gold and uranium are conspicuously absent from the clastic facies of the many sedimentary sequences. Siderophile ores in coarser sediments are replaced by chalcophile mineralization in finer clastics and non-clastics, and some of the largest stratiform copper, cobalt, cadmium, lead, zinc, and vanadium deposits in the World are hosted by Upper Proterozoic formations. Uranium mineralization in strata of this age is quite different to that in Lower Proterozoic formations, and certain of the more significant deposits take the form of unconformity-related ore-bodies. Gold mineralization, of any type, is comparatively sparse in Upper Proterozoic assemblages of sediments.

The boundary between the Archean and the Proterozoic is generally taken at about 2 500 m.y., except in South Africa, where there is a clear change from Archean- to Proterozoic-style crustal development at about 3 100 m.y. Thus, there was a long period of 600 m.y. during which Proterozoic basins formed in South Africa while greenstone-granite terrane was still evolving over the rest of the World. This might be one of the reasons why there is a greater development of auriferous and uraniferous Lower Proterozoic conglomerates in South Africa than elsewhere. The possibility is also present that many metamorphic sedimentary assemblages which have been classified as Archean in other parts of the World might be, in fact, Lower Proterozoic accumulations that were more intensively affected during the last phases of granite intrusion, which extended into the period between 2 500 and 3 100 m.y., as also can be recognized in South Africa. The Sakami Lake conglomerates of Quebec might well be Lower Proterozoic strata, which, because they were involved in the Kenoran orogeny, have been assumed to be Archean. In age, they might be this, if 2 500 m.y. is accepted as the upper limit of this eon, but, in style of formation, they might accord more with Lower Proterozoic sedimentation.

Gold and uranium mineralization in conglomerates both reappear in Phanerozoic times. Table 2 lists some of the occurrences of auriferous and uraniferous conglomerates which have been reported in sedimentary basins formed in the last 700 m.y.

TABLE 2. Auriferous and Uraniferous Conglomerates of Phanerozoic Age

Era	Period	Location of Mineralized Conglomerates	Source
Cenozoic	Tertiary	Miocene, North Pamirs, U.S.S.R.	Boyle (1979)
		Miocene, North Kunlun, China	Boyle (1979)
		Eocene, Klondike, Yukon, Canada	Boyle (1979)
		Eocene, Wind River Conglomerate, Wyoming, U.S.A.	Boyle (1979)
		Paleocene, Pinyon Conglomerate, Wyoming, U.S.A.	Boyle (1979)
		Undifferentiated, South Island, New Zealand	Boyle (1979)
		Undifferentiated, Japan	Krendelev and Pavlov (1972)
Mesozoic	Cretaceous	Harebell Formation, Wyoming, U.S.A.	Boyle (1979)
		Otago region, South Island, New Zealand	Boyle (1979)
	Jurassic	China	Krendelev and Pavlov (1972)
		Undifferentiated, California, U.S.A.	Krendelev and Pavlov (1972)
		Undifferentiated, East Uzbekistan, U.S.S.R.	Krendelev and Pavlov (1972)
Paleozoic	Permian	Laba, Caucasus, U.S.S.R.	Krendelev and Pavlov (1972)
		Ruwe, Shaba, Zaire	Boyle (1979)
	Carboniferous	Horton Group, Nova Scotia, Canada	Boyle (1979)
	Cambrian	Khuzhin Formation, East Sayan, U.S.S.R.	Ruzicka (1971)
		Deadwood Formation, Black Hills, South Dakota, U.S.A.	Boyle (1979)

By far the greater majority of these conglomerates are hosts to alluvial gold concentrations. Uranium is alleged to occur in only two : tertiary conglomerates in Japan and Cambrian conglomerates in the U.S.S.R. In most instances, the Phanerozoic rudites have derived their metal content from the reworking of immediately-underlying and -adjacent Precambrian gold- and uranium-bearing strata. None of these younger conglomerates constitutes major ore-bodies.

The distribution of auriferous and uraniferous conglomerates through time can be summarized as follows :

Phanerozoic	:	mainly gold mineralization, with some rare, alleged uranium concentrations; economic potential much lower than that of Proterozoic conglomerates.
Upper Proterozoic	:	apparent total absence of any significant deposits of gold or uranium in conglomerates of an age between 700 and 1 600 m.y.
Middle Proterozoic	:	very limited development of auriferous conglomerates between 1 600 and 2 200 m.y.; no known uranium mineralization; detrital iron oxides, rather than iron sulphides, most abundant ore mineral; gold-bearing conglomerates virtually disappear immediately after time of world-wide iron-formation; optimum time for Tarkwaian-type mineralized conglomerates.

Lower Proterozoic : auriferous and uraniferous conglomerates extensively developed; economically exploitable facies very restricted, both laterally and vertically; detrital gold, uraninite, and pyrite characteristic constituents of matrices of conglomerates; uranium concentrations apparently greater, relative to gold, in strata between 2 200 and 2 500 m.y.; concentration of gold relatively greater in strata between 2 500 and 3 100 m.y.; optimum time for Huronian- and Witwatersrand-type mineralized conglomerates.

Archean : very limited development of pyritic gold- and uranium-bearing conglomerates during terminal phase of greenstone-belt development; not readily distinguishable from strata in the earliest Lower Proterozoic successions.

AURIFEROUS AND URANIFEROUS CONGLOMERATES IN SPACE

Because the important mineralized conglomerates appear to be time-dependent and are confined, for the most part, to the Lower Proterozoic, their distribution in space also shows restriction to particular tectonic provinces of the Earth's crust. Only in those regions where the Phanerozoic and the Upper Proterozoic covers have been stripped away have Lower Proterozoic mineralized conglomerates been discovered and subsequently mined. In Table 3 are listed the groups and supergroups which house the more important mineralized conglomerates, the maximum preserved thicknesses of these assemblages, and the locations of the areas of development and preservation of the strata within structural provinces.

TABLE 3. Tectonic Settings of Known Auriferous and/or Uraniferous Conglomerates

Country	Supergroup/ Group	Maxm. Preserved Thickness (m)	Location on Elevated Precambrian Structural Province
U.S.S.R.	Krivoy Rog Kursk Karelian	5500 2000 8000	South flank of Ukrainian Shield Southeast flank of Ukrainian Shield Southeast flank of Baltic Shield
Finland	Karelian	5500	West flank of Baltic Shield
Canada	Otish Hurwitz Huronian Sakami Lake	1500 5500 15000 ?	Southeast flank of Superior Province Northwest flank of Superior Province South flank of Superior Province Center of Superior Province
U.S.A.	Deep Lake Phantom Lake Estes	5000 3000 ?	Southeast flank of Wyoming Province Southeast flank of Wyoming Province East flank of Wyoming Province
Brazil	Moeda Jacobina	9000 7500	South flank of Sao Francisco Block North flank of Sao Francisco Block
Ghana	Tarkwaian	2500	Southeast flank of West African Shield
South Africa	Transvaal Witwatersrand Pongola Uitkyk	11000 14000 11000 6000	Southeast flank of Kaapvaal Block Southeast flank of Kaapvaal Block Southeast flank of Kaapvaal Block Center of Kaapvaal Block
Australia	Fortescue	12000	South flank of Pilbara Block
India	Bababudan	?	West flank of Karnataka Block

Almost all of the known conglomerate occurrences are situated on the flanks of structurally-positive blocks which have been subjected to vertical uplift over long periods of time. In the literature, the sites of host-supergroups are generally referred to as being on the edges of shields or cratons, but the term 'craton' has not been applied in the strict serse of its definition, and the elevation regions, away from the shields, are more correctly designated as blocks or provinces, with the shield and satellite blocks and provinces, together, constituting a craton of continental or sub-continental size.

In the case of the Southern Africa Craton, Pretorius (1979) has shown that the central shield region is surrounded by alternating syneclises and anteclises, similar to the patterns developed about the Baltic and Angara shields in the U.S.S.R. Elevation of the anteclises resulted in the uplift and erosion of younger cover-rocks of the platform regions, with the consequent exposure of the Precambrian basement. The blocks and provinces which developed along these anteclises often contain preserved developments of Lower Proterozoic formations. If uplift of the shield region was pronounced, then the likelihood was reduced of Proterozoic strata being preserved amidst the expanse of Archean granites and greenstones which form the ultimate basement rocks. If the shield underwent a relatively intermediate amount of vertical uplift, then Lower Proterozoic assemblages could have been preserved along the outer rims of the shield, down the regional plunge from the centre of maximum elevation. The surrounding anteclises generally have been elevated to a lesser degree than the shield regions, with an enhanced possibility of preservation of Lower Proterozoic strata. The anteclises closest to the shield suffered more uplift than those farther away, as a consequence of which the latter have retained their younger covers, with only a limited amount of Precambrian strata exposed, while the former often represent the ideal sites for the surface expression of relatively extensive exposures of Middle and Lower Proterozoic formations.

An example of a tectonically-influenced distribution pattern can be seen in the Southern African Craton in which the Rhodesia Shield has been elevated to the point where there is maximum exposure of Archean granite-greenstone terrane and a limited development only of Middle Proterozoic formations. To the south, the shield is flanked by the Limpopo syneclise, and then, still farther south, the Kaapvaal Block has been elevated through the Phanerozoic cover. The block is characterized by large tracts of Middle and Lower Proterozoic strata, lying over exposed Archean basement, the areal extent of which is less than that seen on the Rhodesia Shield. All the auriferous and uraniferous conglomerates are restricted to the southeastern flank of the block. The North American Craton has the very large Canadian Shield as its nucleus, with the Huronian formations on its southern flank. The Wyoming Province is an elevated block which might be situated along an anteclise, ringing the shield, and separated from the latter by the Grenville Province, a possible syneclise. The mineralized conglomerates of the Black Hills of South Dakota and the Medicine Bow Mountains and the Sierra Madre of Wyoming, on the Wyoming Block, would then be analagous to the Witwatersrand and other Lower Proterozoic conglomerates on the Kaapvaal Block, with respect to their tectonic setting, but not necessarily in regard to their age or their economic potential.

The preserved maximum thicknesses of the various assemblages of strata containing the mineralized conglomerates are also shown in Table 3. The greater the tectonic uplift which affected the various regions, the less of the original thickness of the particular supergroup was preserved, as a consequence of which the economic potential could have been reduced because of the removal by erosion of possible mineralized rudites in the upper parts of the stratigraphic succession. In the areas flanking the elevated blocks and provinces, there is a likelihood that totally-concealed Lower Proterozoic formations might be present beneath a Phanerozoic cover, which thickens into syneclisal regions. In such negative tectonic provinces, a full range of Proterozoic formations, if such was deposited, in the first place, could be concealed.

Only in the Witwatersrand Basin has extensive exploration, to depths approaching 5 000 metres, been carried out, and the extent of this Lower Proterozoic depository has been revealed to be far greater than indicated by surface exposures. Where mineralized conglomerates have been found in strata of late Lower Proterozoic (2 200-2 500 m.y.) age, the possibility cannot be discounted that, beneath a younger cover, rimming the elevated structural province, formations of the earlier part of the Lower Proterozoic (2 500-3 100 m.y.) might lie undetected. The presence of all host-rocks to Lower Proterozoic mineralized conglomerates has been revealed in areas where a delicate balance between too much tectonic elevation, leading to uplift and erosion of the relevant strata, and too little elevation, resulting in the Lower Proterozoic's still remaining covered by Phanerozoic and other formations, has produced relatively narrow twilight regions in which Archean basement rocks, Lower and Middle Proterozoic strata, and Upper Proterozoic and Phanerozoic platform cover-rocks are all more-or-less equally represented in surface exposures.

GEOMETRY OF BASINS CONTAINING MINERALIZED CONGLOMERATES

Of the many supergroups and groups of Lower and Middle Proterozoic sediments, listed in Table 1 as containing auriferous and uraniferous conglomerates, only a very few have been studied in sufficient detail to permit conclusions being drawn concerning the nature of the basin in which the rocks accumulated and the conditions under which the mineralization took place. In Table 4 are shown the dimensions of the basins in which the conglomerates have been exploited to any degree. Because of blanketing by younger formations, the true strike-lengths and widths of the depositories could be well in excess of those which have been proved by both surface and subsurface investigation. Also, the maximum preserved thickness of strata could be much less than the total thickness of the original pile, as a consequence of uplift and erosion.

TABLE 4. Dimensions of Sedimentary Basins Containing Exploited Conglomerates

Basin	Age (m.y.)	Maxm. Preserved Thickness (m)	Proved Strike-Length (km)	Proved Width (km)
Tarkwaian	1600 - 1900	2500	250	30
Transvaal	1900 - 2200	11000	1100	230
Jacobina	2200 - 2500	7500	230	10
Huronian	2200 - 2500	15000	520	160
Witwatersrand	2500 - 2800	14000	480	180
Pongola	2800 - 3100	11000	150	50

It would appear that the total thickness of sediments and volcanics which accumulated in the Proterozoic basins was of the order of 15 000 metres. Possible maximum strike-lengths could have been up to 1 200 km and widths up to 250 km, to give the basins a distinctly long, narrow geometry. Where only portions of the original basins have been preserved, such as the Tarkwaian, the Jacobina, and the Pongola, the strike-lengths are much shorter, the widths narrower, and the lower parts only of the stratigraphy represented.

The more extensive basins have been deformed according to a pattern of superimposed, interference folds, the axes of which are at a high angle to each other. The present shape of the basins takes the form of a broad arc, with lesser-order folds producing sinuous outcrop traces along the curvilinear, regional strike of the strata. The Huronian arc stretches from the Sault St. Marie area, in the west, to the Noranda area, in the north, the arcuation being concave to the northwest about a regional upwarp axis which trends northwesterly through the Sudbury area.

The Witwatersrand is arcuate about an axis running northwesterly through the Vredefort Dome, the concavity being to the southwest. The arc extends from the Welkom Goldfield in the south to the Evander Goldfield in the east. The strike-length, measured along the outer arc of the deformed basin, is 520 km in the case of the Huronian and 480 km for the Witwatersrand. It is possible that the linear belts of the Tarkwaian, Jacobina, and Pongola are remnant segments of original arcuate geometries of these depositories.

Only in the case of the Witwatersrand and Transvaal basins are sufficient quantitative stratigraphical and sedimentological data available to deduce the three-dimensional geometry of these Lower Proterozoic basins. The southern portion of the Huronian basin has been reworked by the Grenvillian metamorphism, so that it is not possible to determine the nature and extent of the original sediments which were distributed along the outer periphery of the arc. Furthermore, the very limited amount of deep drilling which has taken place outside of the Elliot Lake-Blind River area has precluded attempts to compile isopach, structure-contour, and other such maps, from which the geometry of the original Huronian depository can be estimated. In the case of the Witwatersrand and Transvaal basins, good surface exposures, extensive underground mining excavations, and substantial exploration drilling have allowed profiles to be drawn through the accumulations of sediments and lavas. These two basins are asymmetrical in shape, with a short side, relevant to the depositional axis, characterised by generally higher-energy sedimentation and a long side where lower-energy material was deposited. The short side of the basin appears to have been more active tectonically and the boundaries of the original basin might have been controlled by the development of extensive strike-faults, more-or-less parallel to the depositional axis. Downwarping, rather than downfaulting, might have been the style of deformation of the more passive, long side of the basin.

Figure 1 represents a generalized model of the shape and stratigraphic succession of a typical Lower and Middle Proterozoic basin in South Africa. In addition to the asymmetrical shape, the basin is characterized by a mirror-image stratigraphy in which a basal volcanic and coarse clastic group and a lower coarse clastic and fine clastic group have their counterparts, in reverse sequence, in a terminal volcanic and coarse clastic group and an upper coarse clastic and fine clastic group. The repetition takes place about a pivotal fine clastic and non-clastic group which is located more-or-less in the centre of the complete succession. The shape of the basin is a factor in favouring the prevalence of offlap conditions, on a broad scale, on the short side of the depository and of onlap conditions on the long side.

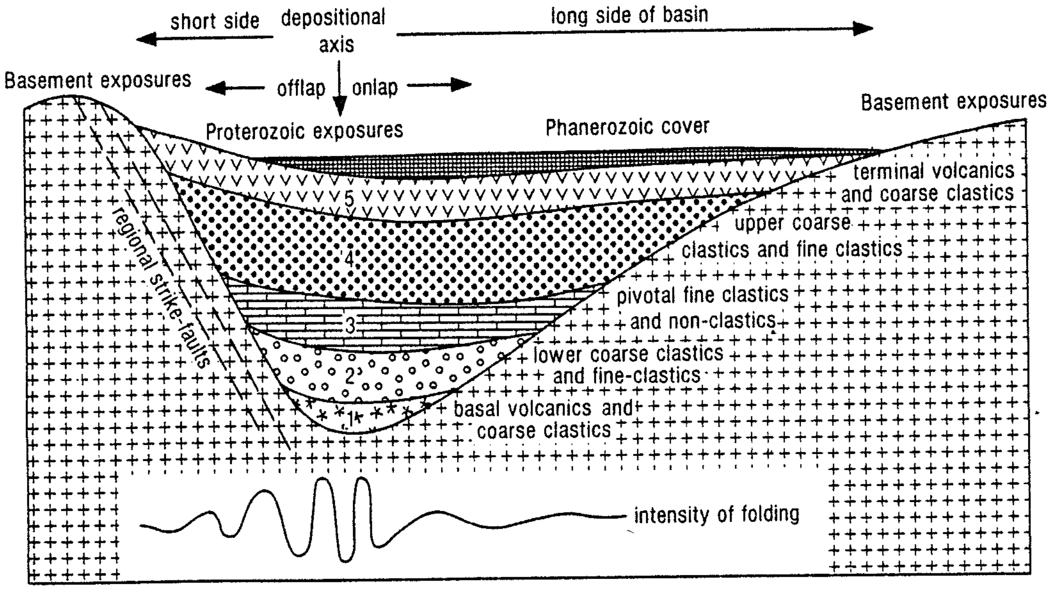

Figure 1 : Geometry and gross mirror-image stratigraphic succession of a typical Proterozoic sedimentary-volcanic basin on the Southern African Craton.

Mineralized conglomerates can be developed in all of the groups, except that reflecting the pivotal low-energy strata. In general, conglomerates are more abundant and have greater concentrations of heavy minerals, including gold and uranium, on the short side of the basin, where higher-energy conditions were responsible for coarser facies being more frequently laid down throughout the total succession and for more reworking of sediments to have taken place. On the long side, because of the generally transgressive relations which exist between the successively-higher formations and the underlying basement, there is a greater tendency for basal conglomerates, basal only with respect to the onlapping formation and not to the whole of the stratigraphic succession, to be preferentially mineralized through reworking of the basement. Auriferous and uraniferous conglomerates of the Tarkwaian, Transvaal, Jacobina, Huronian, and Pongola are located in the lower part of the succession, below the pivotal group of fine clastics and, possibly, non-clastics. In the Witwatersrand Basin, exploited horizons also occur in this part of the succession, but the ore-bodies are of minor importance compared to the conglomerates which are present in the upper coarse and fine clastic group and the terminal volcanic and coarse clastic group. In regard to the stratigraphic position of the more important mineralized conglomerates, the Witwatersrand is different to all other Lower Proterozoic assemblages, and, in this factor, might lie a second explanation, the first being the older age, for the exceptional concentrations of gold.

THE TARKWA GOLDFIELD OF GHANA

In the southwestern sector of Ghana, at the southwestern extremity of the 250-km-long belt of Tarkwaian rocks, is the Tarkwa Goldfield, covering an area of about 20 km, in a north-northeasterly direction, by about 4 km wide, in which 12 larger mines have been operative at one time or another. A long stretch, with no mineralized conglomerates of any extent, follows to the northeast, and at the northeastern extremity of the belt, where it disappears beneath a younger cover, a further development of mineralization is present, but the conglomerates are of limited economic importance. Where mining has taken place, the belt of Tarkwaian rocks takes the form of a synclinorium, 25 km wide, infolded into underlying Birrimian greenstones of either late-Archean age or early-Proterozoic. The general plunge of the structures is to the north-northeast. The conglomerates are well mineralized only in the easternmost syncline. The total strike-length of exposed mineralized rudites, along the limbs of the fold and around the nose, is of the order of 70 km.

The sources of information which have been consulted for this brief summary of the geology of the Tarkwa Goldfield include Junner (1935), Hirst (1938), Sestini (1973), and Boyle (1979).

The auriferous conglomerates are located within the Banket Group of the Tarkwaian Supergroup. This group is up to 700 m thick and overlies the Kawere Group, 400 m thick, which, in turn, rests on the Birrimian basement containing Archean-type gold deposits. Three horizons of conglomerate are developed within a zone that has an average thickness of 40 metres, this zone being 900 metres above the base of the Tarkwaian assemblage. The mineralized horizons are thus not basal conglomerates. The Banket Group is essentially an accumulation of high-energy coarse clastics, represented by conglomerates, diamictites, grits, and quartzites, which have suffered low-grade metamorphism to the chlorite-sericite stage. The best-mineralized horizon is the lowermost of the three. Up to ten bands of rudite are developed over a maximum thickness of 10 metres.

The conglomerate is oligomictic, with more than 90 percent of the pebbles constituted by vein-quartz, the remainder being quartzite and schist. The matrix consists principally of quartz and black sands (mainly hematite, with ilmenite, magnetite, and rutile), while the minor constituents are sericite, chlorite, chloritoid, epidote, tourmaline, zircon, garnet, pyrite, and gold. The footwall quartzites are feldspathic and argillaceous, and the Kawere Group is arkosic. In contrast, the conglomerates and the intercalated quartzites are relatively clean and mature, pointing to reworking. The former have remained poorly sorted. Trough cross-bedding is common in the conglomerate zone, both in the pebble layers and in the intercalated quartzites. The foresets are often delineated by detrital hematite grains. Hematite and other iron oxides also occur disseminated through the matrix.

The gold is mostly concentrated in the basal 20 cm of the lowermost horizon, and the highest values are associated with well-sorted and well-packed, hematite-rich conglomerates which are less than two metres in thickness. Generally, the thinner the horizon, the larger the pebbles, and the higher the quantity of hematite, the richer the gold concentrations. The gold is very fine-grained, averaging 40-60 microns in size. The intercalated quartzites also contain detrital hematite and gold. Paystreaks take the form of lenses of better-developed and better-sorted conglomerate, up to 150 metres wide and 1 000 metres long in the direction of the paleoflow. On average, the paystreaks are about 80 metres wide and 400 metres long. The gold content and the number of conglomerate bands are less in the middle horizon than in the lowermost rudites and are still lower in the uppermost horizon.

The conglomerate zone is constituted by upward-fining fluvial cycles, which, together with the presence of trough cross-bedding, erosion channels, ripple-marks, and the abundance of sand-supported gravels, point to the environment of deposition being that of a piedmont formed by the coalescence of fluvial fans. The payable conglomerate bands are channel lag-gravels or reworked channel- and point-bar rudites, into which took place infiltration of sand, carrying detrital gold, hematite, black sands, and other heavy minerals. The openwork gravels accumulated in braided-stream systems. Paleocurrents flowed from east to west, off the anticlinal elevation of Birrimian basement immediately to the east of the Tarkwa syncline, which latter structure contains the mineralized conglomerates. As the currents approached the axial zone of the syncline, they turned north-northeastwards, to flow parallel to the structural fabric. The relationship between tectonic structures and paleocurrents is also illustrated by the radial flow of streams off the nose of the Anantanfrom anticline, situated to the west of the Tarkwa syncline.

The evidence favours the source of the gold as being the Birrimian schists which form the basement to the Tarkwa Supergroup. No unequivocal provenance has been defined for the abundant hematite that is intimately associated with the gold. Uplift of folds to the east of the Tarkwaian belt created a westerly paleoslope towards depressed tracts developed over synclines. Erosional debris from the positive areas accumulated in the synclinal basins, and, at one particular interval of time, the processes of sedimentation led to the reworking and winnowing of sand-supported gravels, to produce significant concentrations of gold in the matrices of the gravels.

In the context of the stratigraphic model of Figure 1, the whole of the succession in the Tarkwa Goldfield probably belongs to the lower coarse- and fine-clastic unit. Due to either transgressive onlap or non-development, the basal volcanic and coarse clastic unit is not present.

THE JACOBINA GOLDFIELD OF BRAZIL

Mineralized conglomerates have been mined in the southern portion of the 250-km-long Serra da Jacobina range. The belt, in which gold and uranium have been found, is about 45 km in a north-south direction by up to 10 km wide, with the width decreasing progressively southwards. Four mines or prospects have been discovered along a strike of 20 km. The Jacobina group of rocks is contained in a long, narrow fault-block, taking the form of a half-graben in gneissic terrane which might be of Archean age, though the possibility exists that some of the gneisses might represent metamorphosed members of the Jacobina Group. The belt is bounded on the east by the Itaitu Fault, which trends north-south, while the western edge is formed by the limit of transgression of the basal members of the Jacobina Group over the basement. The sediments constitute a tilted clastic wedge, which dips to the east, so that the western extension of the Jacobina assemblage has been uplifted and eroded.

Some of the information which is presented in this summarized description of the Jacobina Goldfield has been drawn from Bateman (1958), Cox (1967), Gross (1968), Robertson (1974), Boyle (1979), and Houston and Karlstrom (1979).

The stratigraphy of the Jacobina Group in the vicinity of the exploited ore-bodies is as follows :

Cruz das Almas Formation	-	+2 000 m	- pelitic schists and well-bedded micaceous quartzites
Rio do Ouro Formation	-	+2 000 m	- well-bedded fine-to-medium-grained quartzites, with basal conglomerates
Serra do Corrego Formation	-	900 m	- quartzites and conglomerates

These formations were believed previously to rest unconformably on the Bananeira Formation, composed of pelitic schists, quartz-muscovite schists, and micaceous quartzites, but it has been shown now that the Bananeira and Cruz das Almas formations are the same accumulation of clastics, duplicated by folding. There is onlapping to the west of successively-higher formations. Stratigraphically upwards, there is also a progressive decrease in the average grain-size of the quartzites. The Cruz das Almas Formation onlaps to the east, but the underlying formations offlap in this direction. The basement on both the eastern and western sides of the belt consists of varieties of granites and gneisses. The strata of the Jacobina Group have been metamorphosed to the amphibole facies, which is a much higher grade than characterizes the Tarkwaian, Huronian, or Witwatersrand.

Three zones of conglomerate development are present in the Jacobina Group : a lower zone, in the Serra do Corrego Formation, about 100 metres above the base of the Jacobina pile; a middle zone, in the same formation, about 300-500 metres above the basement; and an upper zone, forming the lowermost members of the Rio do Ouro Formation, at about 900 metres above the bottom of the succession. The lower zone was deposited on a highly-irregular basement surface, with relief up to 200 metres, in places, and has a thickness of up to 150 metres. The middle zone is the thickest of the three and attains a maximum development of 320 metres, while the upper zone is the thinnest, not exceeding 20 metres. The best mineralization is found in the Main Reef, near the base of the lower zone, which is between 5 and 30 metres thick, and in the Canavieras Reef, in the lower part of the middle zone. Strata between individual conglomerate bands in the three zones, and between the zones themselves, consist essentially of well-bedded and cross-bedded quartzites, often highly micaceous and frequently greenish in colour, because of the presence of fuchsite. All three zones of conglomerate-development represent upward-fining cycles of clastic sediment-accumulation.

Individual conglomerate bands are up to one metre in thickness and are separated by clean quartzites, sericitic quartzites, and arkoses. Because of the high grade of metamorphism superimposed on the sediments, the quartzites are markedly recrystallized. The conglomerates, which house the mineralization, are oligomictic, with the bulk of the pebbles being vein-quartz and the remainder quartzite and schists. The lower zone is characterized by large-pebble conglomerates, with lenses of intercalated small-pebble rudites, while pebble-sizes are large-to-medium in the middle zone and small in the upper zone. The matrix of the various conglomerates is composed mainly of quartz, sericite (15-20 percent), and pyrite (2-5 percent). Minor constituents are : chlorite, tourmaline, zircon, rutile, kyanite, fuchsite, chalcopyrite, pyrrhotite, sphalerite, ilmenite, and molybdenite. Gold occurs within pyrite grains, and uranium is present as uraninite and brannerite. Richer concentrations of the ore minerals are found in channel-fill and channel-bottom-lag conglomerates, particularly where winnowing of cross-bedded sands led to the formation of small-pebble rudites. Lenses of such small-pebble conglomerate are, in the case of the Main Reef of the lower zone, intercalated in large-pebble bands. Gold values are also encountered in the cross-bedded quartzites which act as partings between the conglomerate layers.

Gold mineralization takes three forms in the Jacobina Group : gold in intrusive dykes where these cut across mineralized sediments; gold in quartz veins which have been generated in auriferous pyritic quartzites of the Rio do Ouro Formation; and gold in conglomerate bands in all three zones, but with economic concentrations essentially in the Serro do Corrego Formation. The gold particles are of very small size - between 50 and 100 microns - and have their maximum concentrations in the matrices of well-packed conglomerates, at the bases of thin lag-gravels, and at the toes of foresets in cross-bedded quartzites or conglomerates. Due to metamorphism, the gold has suffered a considerable degree of remobilization. All the gold-bearing rudites carry pyrite, but there is no relationship between the amount of gold present and the intensity of pyrite mineralization.

The Jacobina sediments are thought to have accumulated as a clastic wedge and adjacent to a major strike-fault defining one of the margins of an intracratonic basin. The fault was reactivated repeatedly during the filling of the depository, and there is a close relation between the tectonic history and the processes of sedimentation. A provenance-area of possible Archean gneissic terrane lay to the east of the fault, and erosional debris was transported westwards by rivers from the elevated country in the east, to be laid down in fluvial fans which formed immediately west of the boundary-fault. The conglomerates were formed in a braided-stream system on the fans, with a higher-energy, proximal facies immediately adjacent to the fault and a distal facies at varying distances to the west. Because of subsequent eastward-tilting of the strata, most of the distal faices was uplifted and eroded. With time, there was a progressive decrease in the overall energy-level and a resulting fining of grain-sizes upwards. Sedimentation extended over larger and larger areas, with consequent transgressions stratigraphically upwards, particularly on the western side of the depository. Fluvial sedimentation in the Serra do Corrego and Rio do Ouro formations was succeeded by a marine transgression in the Cruz das Almas Formation.

The evolution of the Jacobina basin would accord well with the generalised model presented in Figure 1. The formations observed in the region of mineralized conglomerates would be the equivalents of the lower coarse and fine clastic assemblage and of the initial stages of development of the pivotal lower-energy accumulations. The stratigraphic positioning of the Jacobina Group and the reduced preserved thickness of the strata point to the fact that the upper members of the total succession are not present.

THE ELLIOT LAKE URANIUM FIELD OF CANADA

The 520-km-long arc, concave to the northwest, of Huronian rocks in the Southern Province of the Canadian Shield can be divided into two main segments. To the north of the first-order, northwest-trending upwarp axis which runs through Sudbury lies the Cobalt Embayment, while to the southwest and west of the axis is the Blind River Embayment. More-or-less midway between the western extremity of the latter segment at Sault St. Marie and Sudbury is the Elliot Lake Uranium Field. This covers a tract of country measuring 35 km east-west and 35 km north-south, from the north shore of Lake Huron, through Elliot Lake, to Quirke Lake. At various times, eleven operating mines have exploited uranium mineralization in Lower Proterozoic conglomerates in this field. About 70 km to the east of the Elliot Lake area is a small isolated development of exploitable conglomerate at Agnew Lake, also within the Blind River Embayment. Relatively insignificant showings of uranium and gold mineralization are present in the Cobalt Embayment, but minable ore-bodies have not yet been located in this segment of the exposed Huronian Supergroup.

The Elliot Lake field is developed in a horst-block between the Flack Lake Fault on the north and the Murray Fault on the south. A synclinorium is present in the horst, plunging at a shallow angle to the west. A syncline which is cut off by the Murray Fault is succeeded to the north by the Chiblow anticline and this is followed, still farther to the north, by the Quirke syncline which abuts against the Flack Lake Fault. Six mines have operated on the north limb of the Quirke syncline, and four on the south limb. The remaining mine is located on the north limb of the southernmost syncline, but, because of the abrupt termination of this structure against the Murray Fault, the possibility exists that mineralization might have been more extensive than that which has been exposed on the small part of the fold preserved north of the fault. Because the zones of preferential development of mineralized conglomerate cut obliquely across the east-west trends of the folds, there is no continuity of such rudites along the strikes of the limbs and round the noses of the folds. Cross-folds are also present, with axes striking north-northeast and northwest. The consequent interference pattern influenced sedimentation and the sites of optimum formation of uraniferous conglomerates.

Sources of information for this general account of the Elliot Lake field include the following : Pienaar (1963), Roscoe (1969), Ruzicka (1971), Robertson (1976), Kimberley (1978), Boyle (1979), Houston and Karlstrom (1979, and Theis (1979).

The maximum development of the Huronian Supergroup is in the Sudbury-Espanola area of the Blind River Embayment, where the constituent groups attain the following thicknesses :

Cobalt Group	6 000 m	conglomerate, arkose, quartzite, siltstone, argillite
Quirke Lake Group	1 500 m	conglomerate, arkosic quartzite, siltstone, limestone, dolomite
Hough Lake Group	3 500 m	conglomerate, subarkosic quartzite, siltstone, argillite
Elliot Lake Group	4 000 m	mafic and felsic volcanics, conglomerate, arkosic grit, quartzite, greywacke, argillite

There is a general thinning of all groups from south to north, so that, in the Elliot Lake area, the total preserved thickness of the Huronian Supergroup has decreased from 15 000 m in the Sudbury-Espanola area to 5 000 m. The upper three groups show well-defined cyclic sedimentation, with each group being represented by lower, higher-energy sediments, lower-energy strata in the middle of the group, and an upper intermediate-energy assemblage. The rocks have been subjected to low-grade, sericite-facies metamorphism in the Elliot Lake field, but, elsewhere, where the supergroup is at its thickest, much higher grades of metamorphism are present.

All the exploitable conglomerates are located in the Elliot Lake Group. The depositional floor on which this pile of volcanics and sediments accumulated was highly irregular in relief, so that the basal members are discontinuous and only locally developed. This applies particularly to the lowermost 2 000 metres of basalt, andesite, rhyolite, arkose, and conglomerate. Above these mixed volcanics and coarse-grained sediments is the Matinenda Formation which hosts the uraniferous conglomerates. Because of the northwards onlapping relation of successively-higher strata, the Matinenda rests directly on the Archean basement in the Elliot Lake area, and the basal assemblage has not been observed. The Matinenda Formation is up to 300 metres thick and is composed essentially of conglomerates, arkosic grits, and quartzites. The conglomerates themselves occur within a zone of sub-arkoses which characterise the bottom 150 metres of the formation. The Matinenda Formation has not been observed to occur in the Cobalt Embayment, and it would appear that sedimentation started later in the northern segment of the Huronian depository than in the portion lying to the west of the regional upwarp through Sudbury.

If the Huronian stratigraphy is fitted into the model depicted in Figure 1, then the Elliot Lake Group would accord with the basal volcanics and coarse clastic group. The pivotal stratigraphic node would be the Espanola Formation, within the Quirke Lake Group.

Three zones of preferential conglomerate development are present in the Matinenda Formation : the Pronto Zone in the south; the Nordic Zone on the south limb of the Quirke Syncline; and the Quirke Zone on the northern limb. These zones strike northwestwards, across the trend of the major folds. The distance, in a northeastern direction, between the Pronto Zone and the Nordic Zone is about 22 km, and that between the latter and the Quirke Zone 10 km. The zones have an *en echelon* arrangement, with the more easterly zones advancing northwards. The Quirke Zone is 9 700 metres long, in a southeasterly direction, by 2 700 metres wide, and the parallel Nordic zone measures 5 800 metres long by 1 800 metres wide. The true dimensions of the Pronto Zone are not known, but it is probable that, before it was affected by the Murray Fault, it was smaller than the Nordic Zone. The northwards onlapping points to the Pronto Zone's having been deposited earlier than the Nordic Zone which, in turn, predated the Quirke Zone. Marked irregularities in the relief of the depositional floor correspond to variations in the nature of the Archean basement rocks, paleovalleys coinciding with the presence of less-resistant lithologies. There is a pronounced thickening of the Matinenda Formation in these paleovalleys, with trend southeastwards. Within these depressions, the conglomerate bands pinch out against basement elevations and are truncated by transgressive overlying formations. Aggregates of conglomerate reach up to 40 metres thick in the depressions, and individual lenses of rudites have widths up to 120 metres across strike and thickness of up to 5 metres. In general, there is thickening of the Matinenda Formation, as a whole, from less than one metre near Quirke Lake to 210 metres at the Pronto Mine. Within the Quirke and the Nordic zones, the conglomerates in the northwestern extremities are more lenticular and variable, while those in the southeast sections are more persistent and continuous.

The uraniferous conglomerates are oligomictic, with vein-quartz pebbles predominating and minor amounts of metavolcanic and chert clasts making up the balance. The pebbles are poorly sorted, tightly packed, and well rounded. The matrix consists mainly of quartz, sericite, feldspar and pyrite, and last-mentioned of which varies between 10 and 25 percent of the matrix. Other minerals present in the conglomerates are zircon, garnet, tourmaline, rutile, sphene, magnetite, cassiterite, chromite, ilmenite, pyrrhotite, sphalerite, galena, molybdenite, cobaltite, arsenopyrite, monazite, uraninite, brannerite, thucholite, and gold. The buckshot variety of well-rounded, coarse-grained pyrite is abundant. The pyrite occurs mainly in the conglomerates and only limited amounts are present in the quartzitic bands which separate the rudites. Thucholite is developed at the tops of fining-upwards sequences of conglomerates and quartzites, and thorian uraninite is common in the hydrocarbon, which takes the form of warty aggregates and thin columnar seams containing uraninite and pyrrhotite.

Cross-bedding is common in the conglomerates and enclosing quartzites, and scour channels frequently occur. Foresets are often defined by pyrite stringers, and detrital uraninite grains are associated with such pyrite. In some instances, the foresets are outlined by layers of uraninite. Pebbles are also seen to be resting on the foresets.

Lithologically, the Matinenda Formation is composed mainly of conglomerates and coarse-grained, poorly-sorted arkosic quartzites and sub-arkoses. In the Pronto Zone, the pebbles in the conglomerates are of cobble size, poorly sorted, and only moderately well rounded. In the Nordic Zone, large pebbles are characteristic, and these are well sorted and well rounded. The progressive decrease in size continues upwards, so that the conglomerates in the Quirke Zone have small-to-medium pebbles, which are well sorted and well rounded. Above the Matinenda Formation, clean, mature conglomerates give way to paraconglomerates which represent either tillites or debris-flows.

The Matinenda Formation has a characteristically-drab colour, indicative of deposition under anoxic conditions, which also favoured the accumulation of detrital uraninite and pyrite. Above the pivotal Quirke Lake Group, the sediments take on light green, pink, and red colours, evidence of the prevalence of oxidizing conditions. Uraninite and pyrite are replaced by monazite and iron oxides in redbeds.

The payshoots of the Elliot Lake field are the broad paleovalley fills of the Quirke, Nordic, and Pronto zones. Within these, paystreaks developed where lenses of a specific type of conglomerate were formed in paleochannels running southeastwards down the paleoslope. The zones have a blunt end up the slope, while their southeastern terminations take the form of elongated, finger-like channels. The best grades of uranium mineralization are present where the conglomerate is massive, well-sorted, well-packed, and has an appreciable content of buckshot pyrite, and where the white vein-quartz pebbles show a pronounced darkening of their rims as the result of radioactive bombardment. Normally, the mineralization is more intense at the base of the rudite. Other indicators of enhanced uranium values are abundant sericite in the matrix and the presence of well-developed cross-bedding. There is a zoning in the nature of the mineralization from northwest to southeast, down the paleoslope. Uraninite, in the upper sections of the zone, gives way to brannerite, in the direction of sediment transport, and this, in turn, is succeeded by brannerite and monazite, and then by monazite and zircon, in the southeastern extremity of the zone. Because of the variation in the hydraulic regime which produced this zoning in the relative concentrations of the detrital minerals, the following changes also take place southeastwards down the zone : the uranium grade decreases; the thorium:uranium ratio increases; the quartz:conglomerate ratio increases; the thickness of the zone increases, mainly as a result of the large volumes of quartzite; the pebbles become smaller; and the clasts become less well-packed. The grains of uraninite in the conglomerate are small, of the order of 50-200 microns, while the monazite grains have a size-range of 200-400 microns.

Two interpretations have been put forward for the depositional history of the Huronian Supergroup in the Southern Province of Canada. The one favours recurrent glaciation, in which the conglomerates constitute the deposits of several major continental-marine episodes, the quartzites the deposits of regressive prograding, fluvial intervals, and the pelites the deposits of post-glacial, transgressive events. The second envisages that the Huronian represents a series of regressive marine cycles that rarely became emergent surfaces of sediment-accumulation. The quartzites are thought to be the products of regressive facies that formed in shallow, turbulent waters in a delta-tidal flat environment. The conglomerates, other than those in the Matinenda Formation, are glacial deposits or extensive debris-flows into a marine environment. The flows could have been triggered off by tectonic activity along major boundary faults of the depository. A cold climate probably prevailed during the formation of the lower part of the Huronian, while hot and humid conditions might have dominated during upper Huronian times.

The conglomerates of the Matinenda Formation are believed to be fluvial deposits in fast-flowing, shallow water. Braided streams moved down paleovalleys, and the lateral migration of the channels led to the coalescence of gravel sheets. There is evidence that one such fluvial system debouched into a near-shore, shallow-water marine environment near the Quirke Mine, on the northern limb of the Quirke Syncline. In the Blind River Embayment, the currents flowed towards the southeast, while in the Cobalt Embayment, the general direction of flow was to the south. A convergence of these two directions took place in the Espanola area, where the Huronian depository appears to have been at its deepest, immediately south of the regional upwarp through Sudbury.

The paleocurrent directions indicate that the source of the uranium and thorium in the Matinenda conglomerates lay to the northwest of the Elliot Lake field. Micro-sedimentological studies have shown that the uraninite, the monazite, the zircon, and the pyrite are detrital, and were transported by rivers from the source-area to the Huronian depository. The brannerite formed by the adsorption of uranium onto titania collectors, such as decomposing ilmenite. The provenance was the Archean terrane lying along the regional upwarp which extends northwestwards through Sudbury. Considerable erosion of the basement must have taken place over this region of uplift, with the result that most of the westwards extension of the Abitibi greenstone belt was removed, and it is from such rocks that the pyrite was probably derived. The uranium and thorium originated in the erosion of the regolith which was present over the Archean granites and gneisses that are represented by two main types : a greypink gneissic granodiorite with abundant greenstone xenoliths and a massive, red, quartz monzonite which has an anomalous uranium content. The uranium was probably derived from a more-differentiated granite which contained relatively greater quantities of potash, microcline, silica, uranium, and thorium.

THE WITWATERSRAND GOLDFIELDS OF SOUTH AFRICA

The preserved portion of the Witwatersrand Basin in the Transvaal and Orange Free State provinces of South Africa forms an arc which is concave to the southeast. The outer rim of the arc is of the order of 480 km long and the width is 180 km. Six goldfields have been discovered along the outer rim, and the possibility exists that still more fields might be present under a cover of younger Proterozoic and Phanerozoic rocks, since the basin remains open to both the east and the south, and no evidence has yet been produced to indicate the original limits of deposition. The positions of the six goldfields, the arcuate nature of the basin, and the depositional isopachs of the upper portion of the stratigraphic succession are shown in Figure 2.

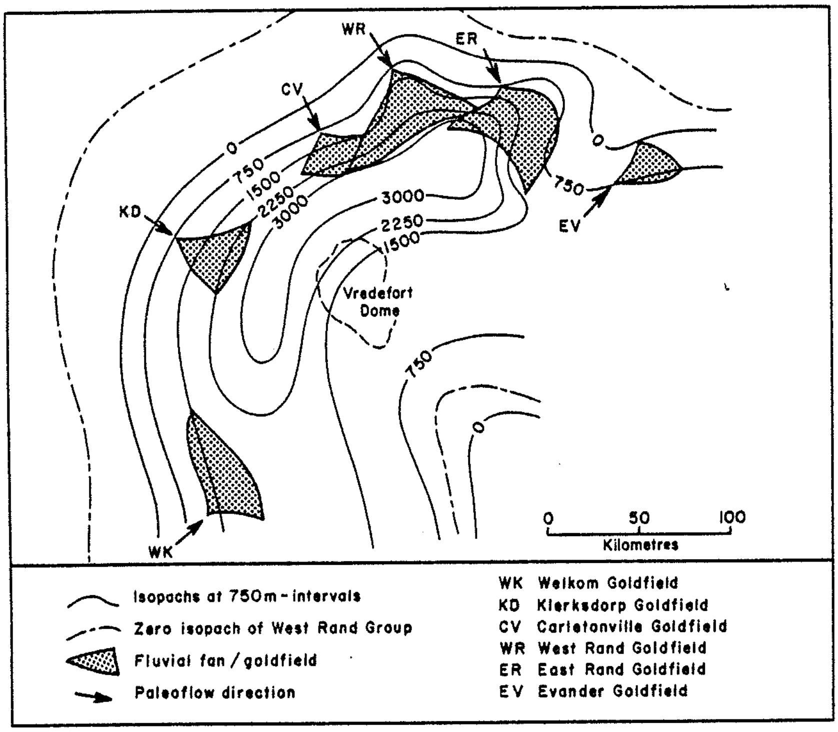

Figure 2 : *Geometry of the Witwatersrand Basin, as revealed by depositional isopachs of the Central Rand Group. The asymmetry of the basin is shown by the distances between the zero isopachs and the depositional axis. Six fluvial fans, hosting the major goldfields, are all located on the short, shrinking side of the depository.*

The shape of the basin shows several similarities to that of the Huronian Basin, but in a mirror-image manner, since the Witwatersrand arcuation is concave to southeast and that of the Huronian depository to the northwest. The axis of arcuation is along a regional upwarp which trends northwestwards through the Vredefort Dome. To the east of this upwarp is the Evaton Embayment, which houses the Carletonville, West Rand, East Rand, and Evander goldfields. This segment of the depository is approximately 220 km long. The Viljoenskroon Embayment is to the south of the upwarp, and the Klerksdorp and Welkom goldfields are situated in this segment, which is at least 180 km in length. The fluvial fans which constitute the goldfields are separated by the following distances, as measured along the curve of the basin : Welkom-Klerksdorp 150 km; Klerksdorp-Carletonville 120 km; Carletonville-West Rand 50 km; West Rand-East Rand 70 km; and East Rand-Evander 100 km. The presence of six separate mining areas in the Witwatersrand Basin is in sharp contrast to only one in each of the Tarkwaian, Jacobina, and Huronian basins.

The depositional isopachs show that, in overall perspective, the basin was shrinking with time, since there is a shift towards the depositional axis of about 60 km between the zero isopach for the lower half of the stratigraphic succession and the zero isopach for the upper half. This shrinking is apparent only on the north-western side of the basin, and the relative positions of the zero isopachs show little displacement on the south-eastern edge. The areal extent of the basin decreased by about 20 percent over this period. The deeper part of the basin occurs within the Viljoenskroon Embayment, and the basal group - the Dominion - is present in this segment only, an analogous situation to the restriction of the Matinenda Formation and underlying volcanics to the Blind River Embayment of the Huronian Basin. An asymmetrical shape is also revealed by the isopachs. The distance between the depositional axis and the zero isopach is much shorter on the northwestern side of the basin than on the southeastern.

The geometry of the Witwatersrand Basin reflects a pattern of superimposed interference folding, as is also the case in the Huronian Basin in the Elliot Lake area. A relatively later series of folds strikes northwestwards and the axes maintain comparatively straight traces. The older folds, parallel to the depositional axis of the depository, have variable strikes because of the bending of these structures about the northwest-trending folds. The basin, as a whole, is a synclinorium. The first-order folds have wave-lengths of 400-500 km, so that the original limits of the basin might be contained between a regional upwarp parallel to, and this distance northeast of, the positive flexure through the Vredefort Dome and a similar upwarp 400-500 km to the southwest. Second-order folds have periodicities of 40-50 km, and the distances between the goldfields might be functions of this wave-length. Third-order folds are spaced at intervals of 4-5 km. Structural domes were produced where longitudinal anticlines intersected transverse anticlines and structural depressions where syncline-syncline intersections occurred. These positive and negative features were episodically active during sedimentation, and their distribution played a considerable role in localising goldfields and in controlling facies variations within the goldfields, which, in turn, influenced the development of mineralized conglomerates and other rock-types.

A considerable volume of literature exists on the geology and mineralization of the Witwatersrand Basin, and the present account has drawn on many of the comprehensive accounts of different aspects. Particularly informative sources include Feather and Koen (1975), Minter (1976), Pretorius (1976), Tweedie (1978), Smith and Minter (1980), and Minter (1981).

A composite stratigraphic column of the Witwatersrand Supergroup gives the following maximum thicknesses :

Klipriviersberg Group	- 2 500 m	- basalts, andesites, conglomerates, quartzites
Central Rand Group	- 3 500 m	- conglomerate, sub-greywacke, feldspathic quartzite, siltstone, shale, volcanics
Jeppe Group	- 1 500 m	- conglomerate, feldspathic quartzite, siltstone, shale, ferruginous shale, calcareous shale, volcanics
West Rand Group	- 5 500 m	- conglomerate, sub-greywacke, sub-arkose, orthoquartzite, siltstone, shale, ferruginous shale, banded ironstone
Dominion Group	- 1 500 m	- andesite, quartz porphyry, rhyolite, tuff, conglomerate, feldspathic quartzite, shaly quartzite

In general, higher-energy sediments are more abundant on the shorter side of the basin, where conditions of offlap also prevailed (Figure 1). Sand-shale ratios are greater, and the percentage of conglomerates is higher. Mineralized rudites occur throughout the succession, from the base to the top, a feature distinctly different to Lower Proterozoic basins elsewhere in the World, in which only one zone within the total fill of the depository hosts auriferous and uraniferous conglomerates. In the Dominion Group, there is one zone of conglomerates which has been mined, in the West Rand Group, one zone, in the Jeppe Group, one zone, in the Central Rand Group, seven zones, and in the Klipriviersberg Group, one zone. Within certain of the zones, up to five separate horizons are exploitable. In addition, in certain localities where the younger Transvaal Supergroup onlaps on Witwatersrand mineralized strata, the basal conglomerate of the former contains reworked auriferous material from the underlying Witwatersrand rocks. In the Welkom Goldfield, four individual conglomerate horizons have been mined in various localities, in the Klerksdorp Goldfield, seven, in the Carletonville Goldfield, three, in the West Rand Goldfield, ten, in the East Rand Goldfield, nine, and in the Evander Goldfield, one.

By far the greater proportion of well-mineralized rudites occurs in the Central Rand Group. Cycles of sedimentation, separated by unconformities, vary in thickness between 30 and 600 metres, averaging 250 metres, and are composed essentially of minor amounts of gravel and major developments of sand, with or without sericite. Argillaceous material caps some of the cycles, which show a fining-upwards sequence. At the base of the cycle, scour surfaces are present, on which pebble-lags or gravel bars accumulated. These are overlain by trough-cross-bedded quartzites, which pass upwards into sub-greywackes and siltstones. The stratigraphic position of the more important conglomerates is unique to the Witwatersrand Basin, since, in the case of the Huronian, Jacobina, Tarkwaian, and other, lesser Lower Proterozoic assemblages, the limited development of mineralized strata occurs relatively close to the base of the succession and not more than half-way up the pile of sediments.

The Witwatersrand succession provided part of the basis for the compilation of the stratigraphic model shown in Figure 1, with the result that the various groups can be accommodated readily into the basal volcanics and coarse clastic unit (Dominion Group), the lower coarse clastic and fine clastic unit (West Rand Group), the pivotal fine clastic and non-clastic unit (Jeppe Group), the upper coarse clastic and fine clastic unit (Central Rand Group), and the terminal volcanic and coarse clastic unit (Klipriviersberg Group). Unlike the Proterozoic basins previously described, the mineralization in the Witwatersrand Supergroup is concentrated above the pivotal unit. The Witwatersrand equivalent of the Matinenda conglomerates of the Huronian would be the Dominion Group and not the more-extensively-exploited horizons of the Central Rand Group.

The mineralized conglomerates consist of about 80 percent pebbles (by weight) which, are predominantly represented by durable rock-types, such as vein-quartz and chert. Polymictic conglomerates carry clasts of quartzite, shale, lava, and schist, in addition to the quartz and chert. The matrices of the conglomerates consist primarily of quartz, sericite, and chlorite, together with a large suite of heavy minerals, the quartz being recrystallized as a result of low greenschist metamorphism. The conglomerates are generally cleaner than the enveloping quartzites, due to winnowing and the removal of the phyllosilicates. More than 70 ore minerals have been recorded from the matrix of the conglomerates, at least 40 of which are clearly detrital in origin. The more significant of these minerals include, pyrite, pyrrhotite, chalcopyrite, galena, sphalerite, arsenopyrite, molybdenite, cobaltite, rutile, leucoxene, ilmenite, zircon, chromite, osmiridium, uraninite, thucholite, brannerite, and gold. Pyrite constitutes up to 15 percent of the matrix and occurs in three forms, one of which is clearly detrital, another an apparently *in situ* development from sulphidic muds in interchannel areas, and the third a recrystallization product of metamorphism. The gold particles range in size between 5 and 100 microns and the uraninite between 15 and 250 microns.

The conglomerate bodies generally take two forms. The more common facies is represented by a channel scour-surface with a thin gravel-lag set in trough-cross-bedded sand, all of which were deposited in a braided-stream environment under relatively high-energy conditions. These ore-bodies are regressive, proximal-facies, placer accumulations. The second type is much less frequently developed, but is of considerable economic importance. The mineralization can be classified as being associated with a transgressive placer which formed on an extensive unconformity that was virtually flat. Distal sediments at the base of a fluvial fan were transgressively redeposited up the paleoslope, by shoreward-advancing waters of the depository, and winnowed in the process.

The best concentrations of gold and uraninite occur in pebble-supported bars that were reworked and winnowed on several occasions. The gold can be preferentially sited in the matrix of the top surface of an individual gravel layer within the bar or on scour-surfaces in the bar, with the heavier minerals being concentrated between successive pulses of gravel accumulation. Generally lower grades of mineralization are present in scour-surface, gravel-lags, which mark the bottoms of channels. Trough cross-bedding, formed by dune-migration in channels and over bars, is associated with better mineralization than planar cross-bedding, which latter structure indicates diverging flow and the rapid dumping of sand. On the smallest scale, gold, uraninite, and other heavy minerals tend to be most abundant along cross-bedding foresets, where the minerals can occur at the top of the foreset, as an avalanche deposit, or at the toe of the foreset, as a result of back-flow turbulence, or on the scoured bottom of the foreset. In all cases, the concentrations are associated with bed-forms that are parallel to the direction of paleoflow.

The Dominion conglomerates, restricted to the Viljoenskroon Embayment, were deposited on a paleoslope that was inclined to the southwest, with the erosional debris coming off the regional upwarp through the Vredefort Dome. Shallow braided streams carried the gravels and sands, and the drainage was controlled by the morphology of the Archean erosion surface, in a manner similar to that of the Matinenda Formation in the Elliot Lake uranium field, except that the relief was not as marked as in the Blind River Embayment and that there was less influence by variations in the lithology of the basement. The basin tended to enlarge during the deposition of the West Rand Group. Subsequent erosion of the material deposited along the edges removed much of the proximal facies of sediments, with the result that most of the preserved strata represent accumulations in distal, lower-energy environments. Marine-shelf sediments, showing tidal influences, predominate, with relatively small amounts of fluvial clastics, the latter having developed as lobular fan-deltas that prograded over the tidal environments. Repeated alternations of transgressions and regressions were responsible for fluvial, beach, near-shelf, and distal-shelf accumulations being represented in numerous cycles of deposition. From the end of Jeppe times, the basin started to diminish in size, and generally regressive conditions prevailed, but with alternations of transgressions and regressions, on a lesser scale, still producing cycles of typically fining-upward strata. During the formation of the Central Rand Group, progradation took place centripetally from all sides of the closed basin. The conglomerates, sub-arkoses, feldspathic quartzites, orthoquartzites, and argillites were laid down on fluvial fans or fan-deltas, the locations of which were determined by the pattern of interference folding, with the fans confined between domes and deposited in structural depressions. Coalescence of the fans took place, to give the false appearance of extensive sheets of uniform gravel, which are, in fact, complexes of superimposed, interfingering, discrete bodies of conglomerate and sand with different compositions, often drawn from different source-areas. Many of the cycles of sedimentation represent responses to repeated tectonic adjustment within, and adjacent to, the depository, which tectonism led to the frequent development of unconformities.

All the significant placer accumulations of gold and uranium were deposited in shallow braided streams. Reworking, under either regressive or transgressive conditions, of the gravels and sands led to the generation of well-mineralized conglomerates. The stream channels have low sinuosity and their depths generally did not exceed two metres. Openwork gravel bars were formed, and the heavy minerals were introduced by subsequent pulses of sand-influx, the arenites migrating in dunes over the gravels. During the periods of non-deposition, at the ends of pulses and cycles of sediment-inflow, winnowing of pebbly sands removed the finer, lighter material and left behind lag-gravels with heavy minerals, mainly pyrite, gold, and uraninite.

Economic concentrations of these minerals are not restricted to the conglomerates. Wherever winnowing of sands took place, the possibility existed that the contained heavy minerals could be left behind as residual accumulations on erosion surfaces, generally unconformities. Consequently, thin layers of gold and other heavy minerals do occur on planes which represent breaks in sedimentation, without any pebbles necessarily being present. Banded pyritic quartzites and orthoquartzites, the latter with single streaks of gold and uraninite, have been exploited and have contributed significantly to the total output. The openwork gravel acted as one form of trap for the heavy minerals in the sand-fraction of the sediment influx, while winnowing acted as another mechanism of concentrating the gold and uranium in areas where no gravels were laid down or were removed entirely during subsequent reworking of the pebbly sand. In addition, a third trapping agency effected the preferential accumulation of gold and uraninite. In low-energy environments, in the distal parts of the fans, algal mats grew, and fine-grained gold and uraninite particles, which passed beyond the gravel traps, were arrested in the mats, where substantial concentrations built up, to form the so-called carbon leaders. Biochemical reworking led to further enhancement of the amounts of these minerals which were fixed in place by the algae. Higher up the paleo-slope, algal activity also developed in abandoned stream-channels, during periods of non-flow and non-deposition of sand, and the bottoms of such channels can also carry gold and uraninite in carbonaceous material.

The individual goldfields represent fluvial fans which stacked upon each other, over long periods of time, downslope from the entry-point of a major river system into the depository, which in Central Rand times, at least, took the form of a closed intracratonic basin. Six river systems have so far been located (Figure 2). A general model of a fan is depicted in Figure 3. The river system was constrained between structural domes, and the fan formed immediately below the point where the river debouched over the elevated ground between the domes. In certain localities, such as the East Rand Goldfield, the fan spread far into the basin, until it abutted against another series of domes. A larger fan, such as this, could have dimensions of 40-60 km radially down the paleo-slope from the entry-point to the edge of the fanbase.

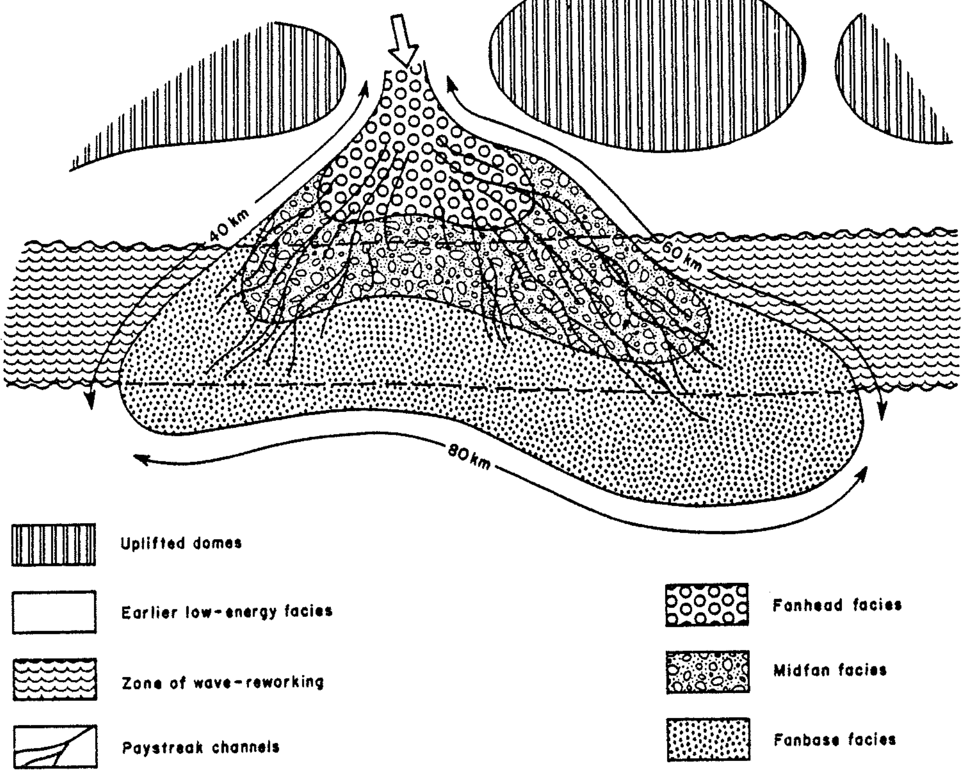

Figure 3 : *Conceptual model of a typical prograding fluvial fan in the Witwatersrand Basin, showing the location of the fanhead, midfan, and fanbase facies and the zone of reworking by wave-action in transgressive depository-waters.*

Three facies can be recognized : (1) a fanhead facies, characterized by the coarsest clastics and lower gold and uranium concentrations; (2) a midfan facies of well-developed, medium-small-pebble conglomerate, with relatively high concentrations of heavy minerals; and (3) a fanbase facies of fine-grained sediment and low percentages of conglomerate, in which lesser amounts of gold and uranium are concentrated. The grain-size of the heavy minerals determined the optimum loci on the fan where they were concentrated by gravity-settling. Depositional conditions were too turbulent and too high-energy to permit the small particles to settle in the fanhead facies. The hydrodynamic regime in the midfan facies provided the most favourable conditions for the heavy mineral-bearing sand to come to rest and to be winnowed subsequently. Only the finest particles, constituting a reduced percentage of the grain-size distribution of heavy minerals, were transported into the fanbase segment. Here, algal mats were effective entrapping agencies for the particles, so that, although the conglomerate-type concentrations are of less importance in the fanbase facies than in the midfan facies, the amounts of gold and uranium won from the peripheral portions of the fan are significantly high. Because of differences in specific gravity and in hydraulic equivalence, the uraninite particles were transported farther down the fan than the gold particles, producing a progressive increase in the uranium:gold ratio down the paleo-slope. The ratio might be of the order of 5 in the lower fanhead and midfan facies, where the pebbles are larger and the pyrite coarser, and it might increase to 25 in the distal fanbase facies where the grain-size of the host-sediments is much smaller, the percentage of conglomerates less, and the presence of carbonaceous material possible.

Paystreaks take the form of braided channels which decreased in frequency down the paleoslope. There is a tendency for the channels to be better developed in two lobes in the marginal thirds of the fan, while the central third, in some instances, has fewer channels and, consequently, lesser amounts of mineralized conglomerates. The importance of the midfan facies as a host to exceptional concentrations of gold and uranium was enhanced by transgression of the depository waters over the fan during periods of stillstand in influx of material from the provenance-area. Wave-action, produced during the transgression, was at an optimum over the midfan and the upper part of the fanbase segments, and winnowing took place,leading to the clean-up of channel sands and gravels and to the transgressive distal type of conglomerate development. The lower reaches of the fanbase segment generally remained below wave-base, a factor favouring the preservation of the algal mats.

In addition to determining the localities within the basin where the fans developed, the structural domes also contributed to the reworking on the material on the fan and the consequent concentration of heavy minerals into residual lag-accumulations. The domes occur along second-order anticlines, both longitudinal and transverse, and the relative amount of tectonic elevation at each intersection of anticline and anticline contributed to the size of the dome. The domes have undergone repeated diapiric-like upward movement, and the sediments flanking the dome have had their attitudes adjusted repeatedly, so that progressively-steeper paleoslopes, off the dome into the basin, resulted with time, leading to generally higher-energy conditions in the upper parts of the succession. With repeated uplift, rim-faults developed around the peripheries of the domes, and the paleoslope took on a step-like profile. The increased gradient of the paleoslope, coupled with the elevation differential over the rim-faults, caused reworking of the earlier sediments into later deposits, particularly along the marginal thirds of the fans, as illustrated in Figure 4. The intimate relation between tectonics, sedimentation, and reworking, leading to economic concentrations of gold and uranium, is the key factor in the formation of a Witwatersrand goldfield.

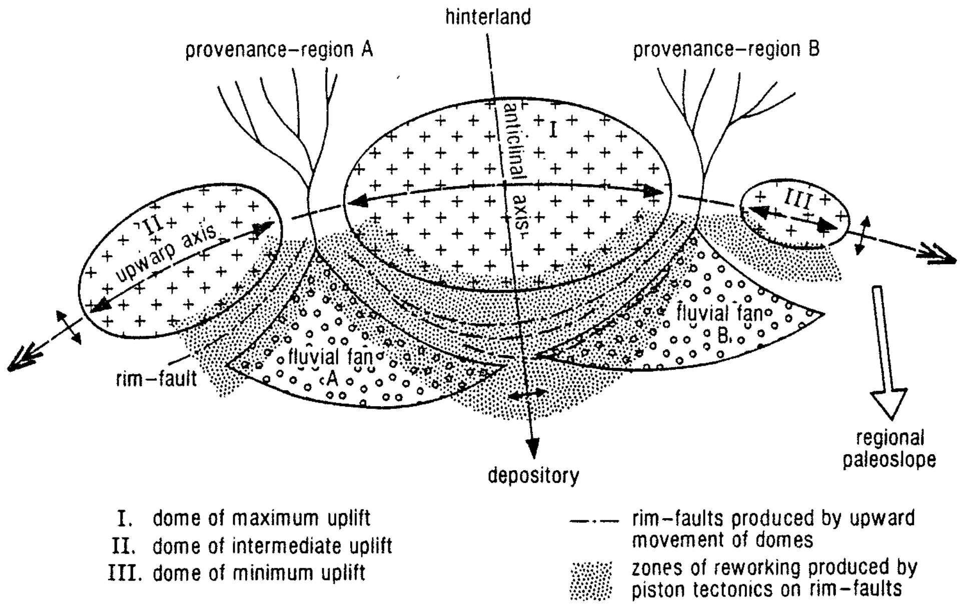

Figure 4 : Influence of structural domes on the location of fluvial fans in Proterozoic basins and on zones of sediment-reworking on unconformities and adjacent to rim-faults produced by diapiric-like rising of the domes.

It is envisaged that the source of the heavy minerals lay in the Archean terrane which surrounded the Witwatersrand Basin and on which the sediments and volcanics were deposited. The gold was probably derived from the erosion of greenstones, which act as hosts to important gold mineralization in various belts in the Transvaal, as they do in the Abitibi belt lying to the north of the Huronian Basin. The uranium had its ultimate source in the granitic component of the Archean assemblage, particularly the more potassic, younger granites. All the major goldfields are located on the northwestern side of the basin, and the paleocurrents indicate that the source-areas lay in this direction. Only small remnants of greenstone are preserved on the northwestern flank of the depository, suggesting that tectonic elevation has been considerable, with the result that granitoid rocks predominant. On the southeastern side of the basin, where there is only minor mineralization, the degree of preservation of greenstones is appreciably higher, pointing to less tectonic elevation, less erosion of potential source-rocks, and less likelihood of appreciable quantities of gold and uranium being transported into the depository.

CHARACTERISTICS OF AURIFEROUS AND URANIFEROUS CONGLOMERATES

Mineralized conglomerates occur in sedimentary assemblages of early-Proterozoic and late-Phanerozoic age, with the interval between being virtually devoid of economically-exploitable ore-bodies of this type. Doubt exists as to the true age of Cambrian rudites in the U.S.S.R., which have been reported to contain both gold and uranium concentrations. The oldest Proterozoic conglomerates are of the order of 3 100 m.y. and the youngest about 1 900 m.y. The Archean does not host mineralized conglomerates which have significant gold or uranium grades, and the Upper Proterozoic, between 700 and 1 600 m.y., represents a conspicuously-lean period for the formation of such deposits. Detrital uraninite disappears from conglomerates after the onset of the period of abundant iron-formation which characterizes the Middle Proterozoic world-wide. Gold concentrations in conglomerates persist for another 300 m.y., but are not to be found after the first development or redbed sequences. The period between 2 200 and 3 100 m.y. is thus the optimum for the generation of auriferous and uraniferous conglomerates and associated mineralized coarse clastic sediments. The most extensive ore-bodies occur in rocks between 2 400 and 2 800 m.y. There is an ill-defined indication that gold might be more abundant in the early members of the Lower Proterozoic and uranium in the later, but conglomerates throughout generally contain variable amounts of both minerals. The Witwatersrand Supergroup of South Africa is the host to the most important mineralized rudites, and a factor which might contribute to this is that Proterozoic-style crustal formation was taking place in the Southern African Craton at a time (2 500-3 100 m.y.) when Archean-style evolution still prevailed through most of the rest of the World.

Crustal stability appears to be an essential component in the array of conditions necessary to permit the conglomerate-type of ore-deposits to form. Only in a stable environment could mature erosional cycles be generated, in which erosional debris could be fed into major river systems that persisted over long periods of time and that discharged into intracratonic depositories.

The time before the formation of the extensive deposits of Middle Proterozoic iron deposits and carbonates was a period of relatively low proportions of oxygen in the hydrosphere and atmosphere, and this overall geochemical environment was favourable to the transportation, deposition, and concentration of detrital uraninite and pyrite. Under the oxidising conditions which prevailed after the onset of iron-formation and red-bed deposition, uranium minerals did not survive in a resistate form, and iron oxides took the place of detrital sulphides. The presence of diamictites in the Lower Proterozoic successions suggests that glacial conditions might have existed on a number of occasions, and the consequent cold climate would also have been conducive to the survival of detrital uraninite and pyrite.

Because of the age of the Lower Proterozoic conglomerates, their exposure is dependent on the removal, by erosion, of a considerable thickness of Upper Proterozoic and Phanerozoic cover, which, in turn, implies that considerable tectonic uplift has been necessary to reveal the presence of assemblages of sediments and volcanics older than 1 900 m.y. Consequently, the known gold- and uranium-fields are all located along the flanks of elevated blocks within the cratons, where Proterozoic formations emerge from beneath a blanket of younger strata. Generally, tectonic uplift has proceeded to a level, in the central parts of the blocks, where all Proterozoic rocks have been stripped away, and only members of the Archean basement remain in exposures. There is a high probability that further Lower Proterozoic basins, with contained mineralized conglomerates, lie concealed down the regional plunge off the central parts of the structurally-positive blocks, in areas where uplift has not been sufficient to bring pre-Upper Proterozoic rocks through the platform cover.

Only the Witwatersrand Basin is sufficiently well known to provide information on the geometry of Lower Proterozoic basins in which mineralized conglomerates accumulated. It would appear that such depositories were at least 600 km long x 250 km wide. They were possibly asymmetrical in shape, with a short side, relative to the depositional axis, on which higher-energy conditions prevailed, and a long side, characterised by low-energy facies. In the case of the Witwatersrand Basin, all the significant ore-deposits are located on the short side of the depository, which was also a region of offlap, in general, a condition favouring the erosion and reworking, into stratigraphically-higher horizons, of previously-deposited sediments. The normally-prevailing onlap relations on the long side were more conducive to burial and preservation of strata, with consequently-reduced opportunities for reworking. The Elliot Lake uranium field would appear to be located on the long, onlapping side of the Huronian Basin.

The maximum thickness of the fill of Lower Proterozoic depositories could have been of the order of 15 000 metres. Lesser figures possibly indicate that portions of the complete stratigraphic succession have been removed by erosion, with the loss of conglomeratic ore-bodies which might have occurred higher in the pile. A conceptual model, based on observations on a number of Lower and Middle Proterozoic basins in South Africa, suggests that the total fill might be subdivided into five groups of strata : a basal volcanic and coarse-clastic unit; a lower coarse- and fine-clastic unit; a middle, pivotal, fine-clastic and non-clastic unit; an upper coarse- and fine-clastic unit; and a terminal volcanic and coarse-clastic unit. Most of the mineralized conglomerates explored are located within the lowermost two units. Only the Witwatersrand Basin has mineralized conglomerates in the uppermost two units, as well as in the two at the bottom of the succession, and it is possibly significant that these upper conglomerates contain appreciably greater quantities of gold and uranium.

The geometry of the basins reflects the structural fabric of the basement on which they were deposited, and there is a close association between tectonics and sedimentation. The paleotopography of the basement was structurally controlled, so that paleovalleys developed along downwarps. In these paleovalleys, river systems deposited gravels and sands, in the latter of which detrital gold, uraninite, and pyrite were present. The structural fabric was repeatedly reactivated during the whole history of infilling, and the same structures which influenced basal sedimentation also played a role in the nature and extent of sedimentation in the closing stages of the history of development of the basin. Of particular importance were structural domes which formed at the intersections of anticlines belonging to two interfering, superimposed fold-trends. The domes exercised a control on the drainage patterns and their episodic, diapiric-like upward movement led to the formation of numerous unconformities on which winnowing processes concentrated heavy minerals. The rising of the domes energized the depositional system, to produce the reworking of material, a process fundamental to the generation of mineralized conglomerates.

The characteristic lithologies of Lower Proterozoic basins which house mineralized rudites are represented by sub-mature sericitic or feldspar-bearing arenites which accumulated under fluvial, deltaic, neritic, and shallow-marine conditions. Thick, deepwater turbidites and chemical sediments were not developed in the depositional environments which favoured the concentration of detrital gold and uraninite. The typical auriferous and uraniferous conglomerate is oligomictic (vein quartz and chert pebbles) and clast-supported, with pebbles generally well-rounded and well-packed, but not necessarily well-sorted. The matrix consists essentially of quartz, sericite, chlorite, and pyrite. The most common heavy minerals include pyrite, zircon, chromite, and leucoxene. Gold occurs in a free form, and the detrital grains are very small, no coarse gold being present. The uranium mineralization reflects the presence of uraninite and brannerite. The matrices of the conglomerates are cleaner than the enveloping arenites and show the effects of reworking and winnowing of light and fine material. Mineralization is usually of a higher grade where trough, rather than planar, cross-bedding is present in the conglomerate and the adjacent quartzose sediments. Concentration of gold and uranium is often at its optimum on unconformities.

Cyclic sedimentation, tectonically controlled, is characteristic of the assemblages in which mineralized conglomerates occur. Such cycles resulted in fining-upward sequences, between unconformities. The gravels in these cycles were deposited in braided streams, either as channel-fill or as bars. The streams were confined to paleovalleys, particularly in the case of rudites which accumulated near the base of the succession, or they spread across fluvial fans or fan-deltas, which were the dominant environment in the conglomerates of the upper part of the Witwatersrand succession. The channels were shallow in depth and of low gradient. Reworking took place under regressive conditions, later streams prograding over previously-deposited gravels, or under transgressive conditions, when the depository-waters advanced over the fan and winnowing was effected by wave-action.

In the Witwatersrand fluvial fans, the optimum sites for higher-grade mineralization in the conglomerates were situated in the midfan sector, where hydrodynamic conditions were favourable to the settling of the small-sized gold and uraninite particles. The parameters normally employed to identify such an environment are also indicators of enhanced concentrations of heavy minerals. Mineralization occurs not only within the matrices of conglomerates, but also as residual lag-accumulations on winnowed surfaces, resulting from the reworking of sands in which the heavy minerals were transported into the basin. Such surfaces are often entirely devoid of pebbles. In the lower-energy fan-base facies, gold and uraninite are frequently associated with carbonaceous matter which was derived from algal mats that acted as traps for very fine particles of heavy minerals. It has been clearly proved that, in the Precambrian conglomerate-type of ore deposit, lithologies other than rudites can contain economically-exploitable amounts of gold and uranium.

All the Lower Proterozoic basins with auriferous and uraniferous conglomerates rest directly on an Archean basement which is believed to have been the source of the heavy minerals. Where a basin was in contact with an earlier Proterozoic assemblage, the conglomerates are either poorly mineralized or barren, except where the later basin reworked, in an area of transgression, gold- and uranium-bearing strata belonging to the earlier basin. The gold is believed to have been derived from the greenstone members of the Archean, while the source of the uranium is thought to have been late, potash- and silica-rich granitoids. The uraninite was probably contained in the extensive paleosols which developed as a regolith over the granites. Such paleosols have been observed to be up to 35 metres in thickness, although the average would be of the order of 5 metres. Quartz and sericite are the main constituents of the paleosol, the sericite resulting from the destruction of feldspars. The erosion of extensive tracts of such paleosol also contributed to the abundance of quartz and sericite which characterize the arenites of the mineralized basins. The stripping away of the regolith, consequent upon tectonic uplift and the initiation of basin-formation, led to the prevalence of mineralized basal conglomerates, such as occur in the Huronian Supergroup in Canada.

The developments of auriferous and uraniferous conglomerates were rare events in the history of sedimentation of Lower Proterozoic basins. Such strata represent the infrequent occasions when the right source-material was being eroded, the right fluvial transporting agencies were in operation, the right depositional conditions prevailed where the rivers debouched, and the right reworking and concentrating mechanisms developed shortly after the heavy-mineral-bearing sands were laid down. Only the optimum combination and interaction of all these factors could culminate in the formation of the most important deposits of gold in the World and some of the greatest concentrations of uranium.

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