

Articles



Ore Deposit Models – 2. Genetic Considerations Relating to Some Uranium Ore Deposits

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Introduction

Since the era of inexpensive petroleum in North America ended in the early 1970s, uranium has assumed an increasing importance as a source of energy. The demand for uranium as a fuel is currently about equal to productive capacity. In the short term, a slight over-supply condition is anticipated. However, worldwide requirements appear likely to exceed supply by about 1987.

The ability to fulfil fuel requirements during the latter part of the 1980s is dependent upon exploration effort and success now. Exploration success, in turn, depends upon intensity of effort expended in environments favourable to deposition of uranium. An attempt is made in this and the following papers to discuss briefly some general aspects of the behaviour of uranium minerals through geologic time and the genetic significance of these aspects in a selection of environments that have been shown by exploration results to host economic uranium concentrations. This article is the first of three on uranium to be written by the author.

Evolution of the Earth and Uranium Concentration

Summary of Geologic Evolution of the Earth

The subject of geologic evolution of the earth has been dealt with by many authors, e.g., Veizer (1973, 1976); Ronov (1964); Roscoe (1973); Cloud (1969, 1971, 1972, 1976); Ronov and Migdisov (1971); Rubey (1951); Ronov and Yaroskewski (1969); Holland (1962, 1974). As may be expected, interpretations vary particularly in regard to the details of the early part of this evolution, but we can be reasonably confident that significant changes have taken place both in the chemical composition of the crust and in evolutionary processes themselves. The following summary attempts to synthesize the work of these authors.

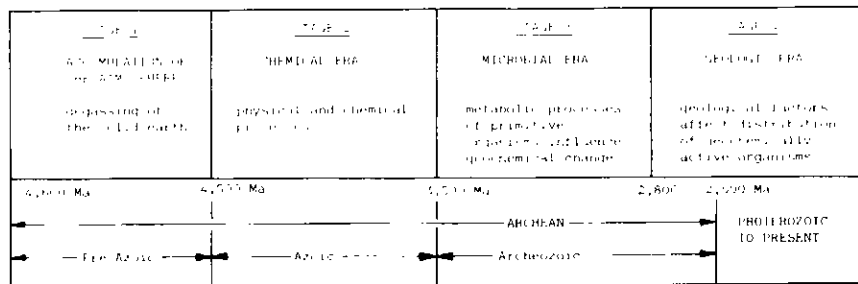
The composition of the upper mantle prior to pre-Azoic time (see Fig. 1) is thought to have approached that of basalt. This basalt is interpreted to be the result of differentiation of chondritic material during the initial stages of formation of the earth. The atmosphere probably consisted of water vapor and nitrogen (~95%) and the remainder of inert gases, and HC1, HF, H₂S, CO, CO₂, CH₄, etc., all derived from the differentiation process.

The decrease in the surface temperature to below 100°C at about 4,500 Ma resulted in condensation of water vapor and formation of oceans, initially of low pH but probably quickly modified upward to 7 to 9

The consequent change in composition of the atmosphere resulted in methane, carbon monoxide and inert gases becoming

predominant. While oxygen may have been produced photo-chemically in small amounts in the upper part of the atmosphere from CO and H₂O, it was used up in the oxidation of NH₃, CH₄ and sulphur. Volcanic activity continued to contribute water vapor and acids which precipitated as an original 'acid rain' that leached alumina, ferrous iron, alkaline earths and alkalis from the exposed rocks. As volcanic activity decreased with time the pH of atmospheric and surface waters rose and hydrolysis replaced solution as the prime weathering process.

Sediments from this time are neither widely distributed nor well preserved. It is probable that there was little topographic relief and few coarse clastic accumulations which, since the crust was essentially mafic, would have been graywackes rather than quartzose sandstones. Nevertheless, secondary quartzites forming in situ as a result of weathering of mafic volcanics may have been widespread. Lithologically recorded Archean time extends from about 3,800 to 2,600 Ma before the present. During the early part of this period continental nuclei were still made up of essentially mafic volcanic rocks, although subordinate intermediate and acid flows are recognized. Weathering of these complexes produced aluminous graywackes. Ferruginous sandstones and, locally, quartzites were also deposited, but neither carbonate rocks nor arkoses were common. Metamorphism of these derived sediments produced the granites which are now seen to separate the ancient continental nuclei. It is estimated by



after Gary L. Walker 1977

Figure 1. Geologic time and Evolution of the Atmosphere

Ronov (1964) that this granitization took place toward the end of the Archean and that 50 to 60 per cent of all granites were developed at that time. The energy required to cause the extensive granitization of the late Archean (and early Proterozoic) is enormous. Its source is a matter for considerable debate. Such extensive and intensive activity has never been repeated.

The tectonic activity of late Archean and early Proterozoic time produced substantial topographic relief, and conglomerates, often wide-spread, were deposited adjacent to mountain ranges and highlands, sometimes upon weathered Archean rocks. Granitic terrain eroded to produce arkoses, quartzose sandstones and illite-bearing shales. Mafic volcanics, or their metamorphic equivalents, contributed graywackes and high alumina shales. Chemical sediments, in addition to carbonate rocks, included siliceous and ferruginous oozes. Organic matter began to be preserved in pelitic sediments.

During the Archean the atmosphere evolved toward the nitrogen-oxygen combination of today, beginning perhaps as early as 3,000 Ma with development of the first Archeozoic blue-green algae and photosynthesis. At this time biogenic oxygen was probably consumed immediately in oxidation of carbon monoxide, ammonia, methane and sulphur as mentioned earlier. Only when the atmosphere was essentially purged of these components could an increase in free oxygen develop, resulting in an increase in the carbon dioxide content of both the oceans and the atmosphere. This change is reflected in the initiation of wide-spread magnesium and calcium carbonate deposition.

At about 2,200 Ma, the oxygen content of the atmosphere passed through a critical

level. There is some question what this was, but it is certainly small, perhaps in the order of one per cent of the present concentration. Exposure of ferrous iron to the atmosphere resulted in the formation of red iron oxides (Walker, 1977, Cloud 1976) in continental sediments. This is perhaps the most significant indicator of oxygen level in the evolving atmosphere. It will be noted that red iron oxides exist in Archean marine rocks, but in this environment they are considered indicative of locally available biogenic oxygen rather than general atmospheric oxygenation (Mason and Von Brunn, 1977).

Widespread oxidation of iron would have provided an oxygen demand of enormous size (one tonne of Fe_2O_3 contains about 300 kg oxygen). Carbon monoxide and methane in the atmosphere, and ammonia in sea water, also presented an oxygen demand and these factors may have delayed the oxidation of sulphur and hydrogen sulphide in ocean waters. Sulphate deposits (anhydrite and gypsum) in sediments are rare prior to 1500 million years and become common during Palaeozoic time. When these demands had been satisfied, the oxygen content of the atmosphere began to increase through time to the present 20.9 per cent.

An approximate equilibrium between carbon dioxide in the atmosphere and in the ocean was probably attained shortly after oxygenation of the atmosphere, although a gradual decrease in CO_2 content through Palaeozoic time, with a sharp reduction at the beginning of the Mesozoic, is indicated by an increasing Ca/Mg ratio in carbonate rocks.

The Behaviour of Uranium Through Time

It is very likely that the availability, mobility and probability of uranium concentration have changed through time with the changing physico-chemical conditions outlined above (Fig. 2).

In pre-Archean time, the availability of uranium in the crust would have reflected the average abundance of the metal in basaltic rocks. Basalts of all ages today contain, on average, less than 0.6 ppm uranium. Extrapolation based on the half-life of ^{238}U and ^{235}U to about 4,500 Ma, and assuming no 'enrichment' in the basalts sampled, indicates that the original uranium content would have been about 1.5 ppm. As long as the crust was essentially basaltic, the probability of developing uranium concentrations that might be of economic interest (500 ppm or more) appears to be very low. Weathering of basalts prior to Archean time probably resulted in solution of uranium by 'acid rain' and re-precipitation on neutralization of runoff on entry into the primordial seas, so some minor enrichment of uranium in early sediments seems possible.

During Archean time, hydrolysis of silicates became the predominant weathering reaction. Uranium minerals, e.g. juvenile UO_2 , would be essentially insoluble and, although not notably enriched in the source rock, could be expected to report as a heavy mineral in clastic sediments.

Granitization of sedimentary piles with introduction of volatiles, alkalis and metals, appears to have been necessary to provide the enrichments in source rocks required for development of palaeoplacers of the Dominion Reef and Elliot Lake type. Suitable source granites may have developed as early as 3,100 Ma (Allsopp, 1964), and more were added in the late Archean and early Proterozoic. Evidence for primary hyd-

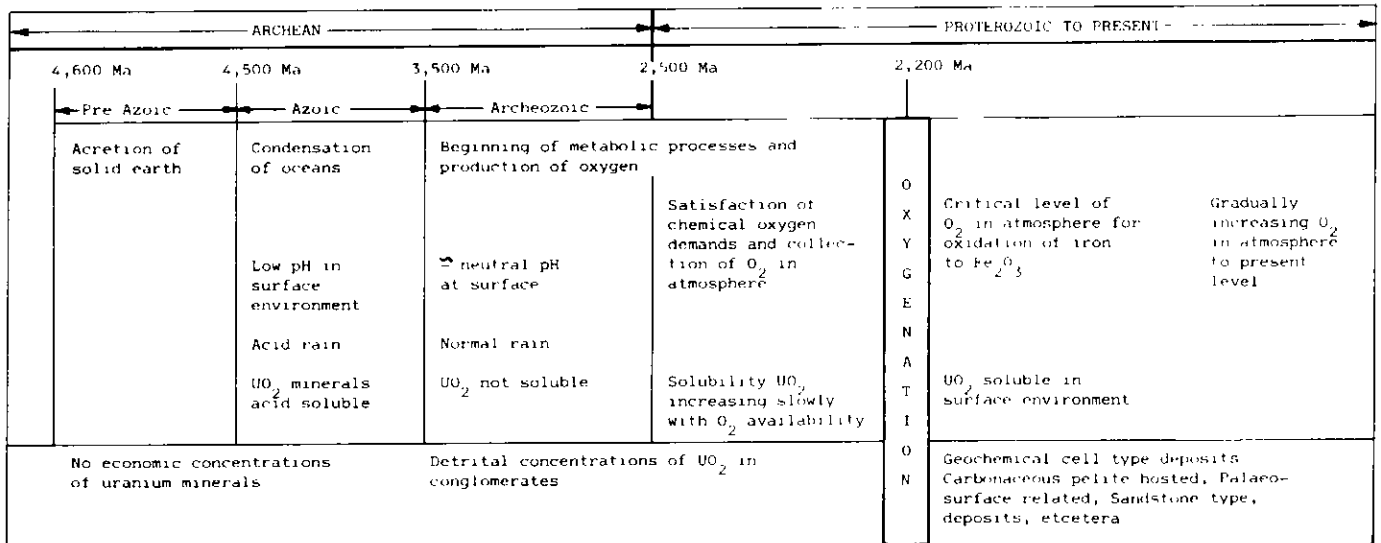


Figure 2. Behaviour of Uranium through Geologic time

rothermal or volcanogenic uranium concentrations of economic interest in either the Archean or early Proterozoic has yet to be found. However, sufficient uranium was available in the more evolved magmas (syenites, etc.) beginning in middle Proterozoic time, to produce volcanogenic deposits, such as near Baker Lake in the District of Keewatin.

It has been noted earlier that oxygen concentration in the atmosphere in early Proterozoic time rose through a critical level at about 2,200 Ma. This change is of major significance in the genesis of uranium ore deposits, since from that time onward simple uranium oxides were no longer stable in near-surface environments. Non-thorian uraninites could no longer report as detrital minerals in alluvial deposits, and formation of conglomerate ores of the Dominion Reef and Elliot Lake type became impossible. With increase in atmospheric oxygen content the mobility of uranium became similar to that known today. The metal entered surface and ground waters in the zone of weathering some to be carried by surface drainage to the sea where it was concentrated in shales or carbonaceous pelites, occasionally to economically interesting levels, or dispersed into the ocean waters. Ground waters carried uranium into anoxic conditions at depth where concentration through reduction was possible.

In the near-surface environment, other uranium concentrations have developed in coals, in calcretes and gypcretes, and syngenetically in palaeostream channels due to reducing conditions associated with decomposing organic material.

The mobility that uranium attained with oxygenation of the atmosphere permits a variety of 'geochemical cell' concentrations including classic 'roll-front' and 'tabular' sandstone-type deposits of the western United States and the palaeosurface-related deposits of the Athabasca Basin. Additionally, deposits near Limoges, France, show evidence of concentration or at least enrichment, due to downward-flowing uranium-bearing waters. Several of the Portuguese deposits also appear to be the result of per descensum concentration.

Exploration results to date suggest that there are two such periods of maximum primary chemical concentration of uranium in sedimentary rocks. The earlier concentration took place in post-oxygenation Apebian time, probably between 2000 and 1,800 Ma (e.g., Saskatchewan, Northern Australia). The second period is in early Proterozoic time, typified by the Swedish Alum shales of Middle and Upper Cambrian time.

Metamorphic recycling of uraniferous sediments produced further enrichment in

portions of the resulting granites. The 'shale-granite-shale' cycle could be repeated several times.

Metamorphism of uranium-enriched rocks of lower Proterozoic age (post-oxygenation Apebian or younger) has been noted to produce hydrothermal veins (metamorphic hydrothermal) that show economic promise. Metamorphic hydrothermal uranium-bearing polymetallic veins and simple uranium (uraninite) systems that date from Proterozoic to Cenozoic time are also known.

Classification of Uranium Deposits

General

In this paper uranium deposits will be classified in two general categories: 'Major Deposits' and 'Minor Deposits' (Table I). The Major Deposits include Precambrian conglomerates and sandstone-hosted ores of

the western United States type. Vein-type deposits are also listed in this group. Originally the vein-type designation was applied to mineralization deposited from classical (Lindgren) hydrothermal solutions. More recently the Athabasca and Northern Territory, Australia, deposits have also been included. All other deposits are classified herein as 'Minor Deposits'.

Other classifications of uranium deposits have been proposed (e.g., McMillan, 1976, 1977; Barnes and Ruzicka, 1972; Derry, 1980). There is by no means complete agreement on what classification or genetic model may be appropriate for individual ore deposits or types of ore deposits. My experience suggests that classification of uranium ore body types with reference to their relationships to surface or deep seated processes provides useful guides for exploration.

Table 1

Another Classification of Uranium Deposits	
Major Uranium Deposit Types	
Surface Related	Deep Seated
1. Pre-oxygenation conglomerate	
2. Sandstone-hosted geochemical cell a) Roll front b) Tabular c) Channel - epigenetic d) Channel - syngenetic	
3. Carbonaceous pelite-hosted a) Syngenetic ores b) Protores c) Subsequently enriched protores 1. Weathering	2. Metamorphism 3. Autogenous Processes
4. Palaeosurface-related	
Minor Uranium Deposits Types	
Surface Related	Deep Seated
	5. Magmatic a) Plutonic 1. Internal Enrichment 2. Peripheral concentration 3. Classical hydrothermal b) Shallow intrusive 1. Degassing channels 2. Quenched gas hydrothermal 3. Enriched extrusives (protore) 4. Enriched dykes, sills, etc. 5. Carbonate 6. Alkaline complex exotic differentiates c) Post-intrusive convection cell 1. Cooling magma-related - hydrothermal 2. Radiogenic heat-related - hydrothermal
	b. Metamorphic a) Anatectic b) Contact c) Hydrothermal
7. Uraniferous coals	
8. Calcrete and gypcrete-hosted	
9. Sedimentary phosphates	
10. Surface enrichments	
11. Other	
	12. Other

Modelling Criteria

The approach that will be taken in this paper is based on the fundamental requirements that must be met if unusual concentrations of metals are to develop. These essentials are: an adequate source of readily available metal(s) within the environment under consideration; an effective collection and transportation system while the metal(s) are readily available; exposure of the metal(s) to an environment where conditions permit their deposition and concentration; preservation of that concentration through time (Fig. 3). If any one of these requirements is not fulfilled, there can be no ore body.

A variety of models may be proposed for a given ore body or type of ore body, and each may have its merits. In this discussion, however, one model will be presented for each of the deposit types considered, and it is the model which best fits my experience and particular biases.

These models are not descriptions of particular ore bodies, but general frames of reference which may be applied to the understanding of, and exploration for, the deposit type. However, reference to particular deposits by way of illustration is unavoidable.

It is important to emphasize that use of formalized models of ore deposits should be undertaken with some care since many of them, uranium concentrations in particular, are likely to be polygenetic and remarkably sensitive to physical and chemical modification due to metamorphism, weathering, sub-surface fluid movement and, under appropriate conditions, to radiation and thermal effects originating in the radioactive ores themselves.

Application of this modelling approach to the study of uranium ore bodies results in the classification given in Table I, which is based on what appears to be the original mode of enrichment with reference to modifications likely in the environment under consideration.

Major Uranium Deposits

A review of the uranium deposits of the world that have produced uranium in significant quantities shows that the majority of them lie in geologic environments that suggest a definite genetic relationship of economically significant concentrations of the metal with near-surface processes.

Deep seated geologic processes are an important part of the geochemical recycling of uranium. But, although there are notable exceptions, these processes generally have not produced deposits and reserves comparable in size to those contained in the surface-related deposits.

Uranium production of approximately 130,000 tonnes U has been realized from pre-oxygenation Precambrian

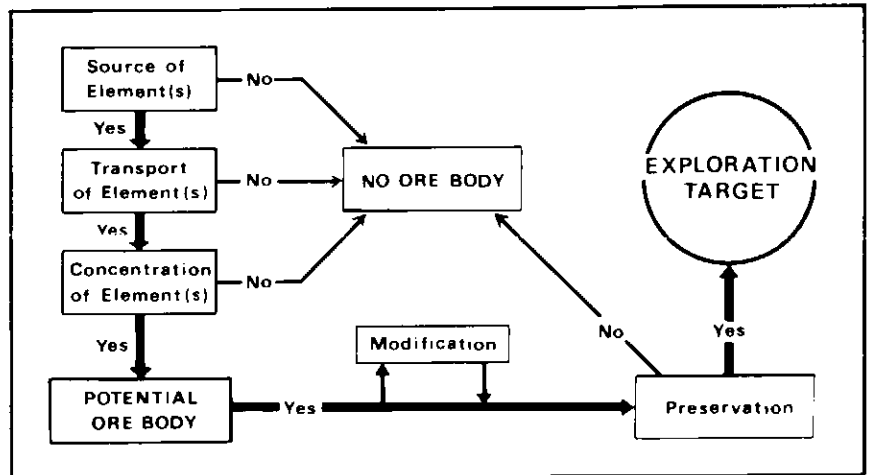


Figure 3. Conceptual Model for the formation of an ore deposit

conglomerates of the Elliot Lake area, Canada, and the Witwatersrand in the Republic of South Africa.

Sandstone-hosted ores are the most important source of uranium in the United States. Production to date totals about 300,000 tonnes U. Similar types of deposits, some of major proportions, have been discovered in other areas (for example Argentina in South America, Niger in Africa).

Some post-oxygenation *Proterozoic sediments* are observed to be particularly enriched in uranium. Sandstones, shales, carbonaceous pelites, and detrital (?) carbonate horizons, that contain apparently syngenetic concentrations of uranium, have been identified in many parts of the world. With a few notable exceptions, carbonaceous pelites seem to be the most favourable host rocks. Reasonably assured reserves in this environment presently are approximately 350,000 tonnes U.

Exploration in Saskatchewan along the unconformity between Helikian age (~1450 Ma) continental sediments and older Precambrian basement rocks, has proven to be particularly successful in locating high grade concentrations of uranium in either or both basement and cover rocks adjacent to the paleosurface.

On the basis of production realized and assured reserves, deposits in these four environments are the most important sources of uranium.

Minor Uranium Deposits

Notwithstanding economically significant uranium production or reserves in some individual deposits of the kinds mentioned in the following paragraphs, none of these types has aggregate production or reserves recoverable under current economic conditions comparable to any one of the four major types listed earlier.

These remaining deposit types can be divided into two general classes: those formed directly or indirectly as the result of surface-related (weathering) processes and those related to 'deep-seated' magmatic or metamorphic processes. Deposits related to magmatic activity include concentrations, for various reasons, within magmatic material, concentrations peripheral to intrusions as a result of pneumatolitic activity, and classically defined hydrothermal veins.

Uranium mineralization can also be associated with extrusion of lavas and energetic degassing related to volcanism and shallow intrusion. Circulation of meteoric waters driven by thermal energy related to intrusives can also result in veins that may be classified as hydrothermal. Mineral deposition in both ascending and descending segments of such a convection cell is possible (Fehn *et al.*, 1978).

In addition to contact metamorphic mineralization, metamorphic processes can result in derived fluids collecting, transporting and depositing uranium in fault or fracture systems in concentrations of potential economic interest. Metamorphic-hydrothermal deposits of this kind are found, for example, in northwestern Europe and northeastern Canada.

In situ granitization of uranium-enriched shales may produce 'anatectic' deposits such as at Charlebois Lake, Saskatchewan, or near Rössing in Namibia.

In the surface-related minor deposit category a number of types of mineral concentration have resulted in commercial production or will be possible producers in the near future. Among these are uranium-enriched coals of various Phanerozoic ages, Late Tertiary and Recent calcretes, gypcrettes and secondary enrichments.

Sedimentary phosphates are known to contain ten to 100 ppm uranium. None has

been mined strictly for its uranium content and projections are that, almost without exception, sedimentary phosphates can produce uranium only as a relatively high-cost by-product.

A selection of other varieties of uranium concentrations exists as a result of surface-related processes. The possibility of production from uraniumiferous organic lake-bottom sediments is being studied in some taiga environments. Certain guano deposits carry more than 1,000 ppm uranium. Residual phosphates in karst structures may be sources of limited but significant quantities of the metal. Additional locally important uranium concentrations may form because of special conditions of geology and climate presently unknown or as yet undefined. Nevertheless, the most productive of these environments appear to be reasonably well delimited.

Review of Major Uranium Deposit Types

Proterozoic Conglomerates

Pre-oxygenation Proterozoic conglomerates have been identified in a total of eight localities in North and South America, Southern Africa and Australia. Additional ores may occur in India but data are scarce.

Uranium production has come from the Elliot Lake conglomerates where it is the only commercial product, and from the Witwatersrand gold mines where the metal is recovered chiefly as a by-product or co-product. None of the other pre-oxygenation conglomerates has been the source of commercial production although certain of the Brazilian conglomerates have uranium concentrations that approach economic grades. The Australian conglomerates carry, on average, less than 50 ppm U. Although the distribution of pre-oxygenation Proterozoic conglomerates is relatively restricted, over 25% of the uranium mined to 1979 has come from these rocks in the Canadian Lower Huronian and the South African Witwatersrand Basin.

Uranium has been produced from four palaeo-drainage systems in the Huronian rocks of the Elliot Lake area. In the Witwatersrand Basin, uranium has been recovered from mines in five of the six fans that have been exploited for gold.

Source of Metal. The uranium minerals concentrated in both the Canadian and South African conglomerates were derived from uraniumiferous granitic rocks in the sediment source areas.

Release of Metal. Uraninite grains were probably released from the granites as a result of chemical decomposition of the feldspars (hydrolysis) and subsequent mechanical disintegration of the rocks. As mentioned earlier, prior to about 2200 Ma the

atmosphere was essentially anoxic. The surface environment was electrochemically reducing to the extent that uraninites, particularly those containing more than 1 to 2% ThO₂, were not soluble in runoff or ground water. It was possible, therefore, that uraninite could accumulate in eluvial and alluvial environments in the same fashion as other heavy mineral grains.

Transport of Metal. The mineral grains freed by hydrolysis and mechanical weathering moved with other sediment from the provenance area in the drainage system as part of the bed load.

Concentration of Metal. Uraninite collected preferentially in locations within the drainage system where energy conditions were favourable. The subject of the energy requirements for deposition is well covered in papers by Pretorius (1976) and Theis (1979) among others.

Mineral distribution within the conglomerate units is a reflection of these energy conditions and is often indicated on a broad scale by changing uranium-thorium ratios both along and across the axis of deposition of the units and also, on a smaller scale, vertically through individual conglomerates (Robertson, 1962). The oldest conglomerate ores, such as those of the Dominion Reef (Lower Witwatersrand Super Group) and the Elliot Lake camp (basal Huronian Super Group) appear to be the result of high energy concentrations. These lie within coarse clastic sediments of the main drainage axis of the fluvial system or important channels of the alluvial fan.

Reworking of older conglomerates exposed along the margins of the Witwatersrand basin during structural down-warping and regression is discussed by Pretorius (1976). A similar down-warping of the Elliot Lake Basin as sedimentation progressed is reported by Robertson and Douglas (1970). Erosion of some parts of the ore beds is observed in both the Nordic and Quirke fans but presently economic reconcentration in younger (Middle Mississagi) sediments is not known.

In the part of the Witwatersrand Basin stratigraphic section above the Dominion Reef evidence of primitive plant growth becomes progressively more common in these pre-oxygenation Proterozoic sediments. Both uranite and native gold were collected in the lower energy environments of the mid-fan and fan base by the 'golden fleece' effect of these algal mats. Similar low energy detrital mineralization has not been recognized in the Huronian of Canada although Theis (1979) reports carbon bands in mid-fan conglomerates from Quirke Lake that contain notable enrichment of detrital grains of uraninite. There is also evidence of chemical replacement of organic structure

in the Witwatersrand Basin algal mats by gold and uranium. This has not been noted in the Canadian ores, perhaps because exploration seems to have been confined largely to the high energy fluvial and fan head environments.

The conglomerates of Belo Horizonte, Brazil (Ramos and Fraenkel, 1974; Robertson, 1974), are stratigraphically high in the pre-oxygenation Proterozoic section. They lie within less than 200 metres of the base of the red hematite ores of the Itabira Formation. The association of organic matter with uranium values has been observed but, due to the relatively high energy fluvial environment of deposition, mineral concentration appears to be chiefly by mechanical segregation in the bed load.

The pre-oxygenation Proterozoic conglomerates at Jacobina, Brazil, are less well developed than those mentioned above. The environment is relatively high energy braided fluvial. The conglomerates are notably auriferous (White, 1961) but carry only low uranium values. The source area was apparently uranium-deficient.

Modification. The conglomerates from which the bulk of production has been realized are very mildly metamorphosed. There is little redistribution of metal values although some mobility is evident. Theis (1979) shows that the Elliot Lake 'brannerites' are the result of replacement of TiO₂ by UO₂. This may have been a diagenetic process.

Dynamic metamorphism of Huronian conglomerates at Agnew Lake, Canada, has resulted in stretching of pebbles accompanied by greenschist grade thermal metamorphism. There has been only slight redistribution of uranium.

Metamorphism sufficiently strong to destroy a conglomerate as a definable rock unit could be expected to result in dispersion of the uranium. Such a situation has not been identified.

Preservation. Erosion and severe metamorphism are the mechanisms most likely to destroy deposits of this nature. The host rocks therefore must lie in regions of the crust that have been tectonically stable since deposition.

Conclusion

The distribution of pre-oxygenation Proterozoic conglomerates is rather restricted on a world wide basis. Most of the potentially productive basins appear to have been identified and explored rather intensively. Thus, while this environment has proved to be a notable source of uranium and the presently known ore fields will continue to produce into the twenty-first century, the prospects for additional discoveries of the scale of the Elliot Lake or

Witwatersrand types do not appear to be particularly good. Nevertheless, more exploration effort for 'distal-type' (Pretorius, 1976) concentrations may be warranted in the upper part of the pre-oxygenation Proterozoic section wherever it is known.

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MAC Short Course

FLUID INCLUSIONS: Petrologic Applications

May 7-10, 1981,
The University of Calgary, Alberta
Precedes GAC/MAC joint meeting

Designed primarily for petrologists, this course will provide instruction in how to obtain and use data from fluid inclusions in the interpretation of igneous and metamorphic rocks.

The course will be structured around use of the cooling and heating stage, with which temperatures of observed phase changes in individual inclusions are measured. Composition and density of the fluids are determined from these data by reference to known or theoretically obtained PVT properties of the fluids.

Instruction will include a summary of PVT data for fluids in systems containing CO₂, CH₄, H₂O, and salts. Practical aspects of interpreting the data will be illustrated with use of closed circuit television and by videotapes. Applications of fluid inclusion studies in igneous and metamorphic petrology will be emphasized, and those in ore petrology and diagenesis will be summarized.

Contributors to the lectures and chapters of the short course publication include R.C. Burruss, M.L. Crawford, L.S. Hollister, J.R. Holloway, E. Roedder, E.T.C. Spooner, J. Touret and A. Weisbrod. The organizers of the short course are M.L. Crawford, L.S. Hollister and E.D. Ghent.

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Registration will be limited to 50 delegates.

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Errata

Article by C.E. Blackburn, volume 7, no. 2, page 67, line 12 of Figure 3b and 3c caption should read: - - - "in Figure 3c field A alone encompasses low-potassium tholeiites, field B alone encompasses calc-alkali basalts - - -"