MASTER

National Uranium Resource Evaluation

**SEDIMENTATION OF THE BASAL KOMBOLGIE
FORMATION (UPPER PRECAMBRIAN-CARPENTARIAN)
NORTHERN TERRITORY, AUSTRALIA: POSSIBLE
SIGNIFICANCE IN THE GENESIS OF THE UNDERLYING
ALLIGATOR RIVERS UNCONFORMITY-TYPE URANIUM
DEPOSITS**

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October 1979

PREPARED FOR U.S. DEPARTMENT OF ENERGY
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SEDIMENTATION OF THE BASAL KOMBOLGIE FORMATION
(UPPER PRECAMBRIAN-CARPENTARIAN) NORTHERN TERRITORY, AUSTRALIA:
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ALLIGATOR RIVERS UNCONFORMITY-TYPE URANIUM DEPOSITS

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ABSTRACT

The 1400-1500 m.y. old Kombolgie Formation of the MacArthur Basin of the Northern Territory overlies or has overlain unconformity-type uranium deposits including Jabiluka, Ranger, Koongarra, Nabarlek and the small deposits of the South Alligator River Valley. A brief study of the basal portion of the formation showed it to consist entirely of mature conglomerates and quartzose sandstones. Analysis of the bedding types (planar cross beds, trough cross beds and parallel beds) and other sedimentary structures (mainly ripple marks and parting lineation) fit a braided alluvial plain model. A paleocurrent study utilizing about 400 measurements from nine localities located along the westward-facing 250 kilometer-long erosional escarpment of the Arnhem Land Plateau showed the dominant paleocurrent trend to be from west and northwest towards the east and southeast, with local divergence. The data and interpretation presented here are relevant to the supergene model of uranium deposition at the unconformity, for they add to the suggestion that additional uranium deposits similar to Jabiluka Two may underlie the Kombolgie Formation eastward from the present escarpment.

INTRODUCTION

The 1400-1500 m.y. old Kombolgie Formation and equivalent units cover about 200,000 km² in the MacArthur Basin at the top end of the Northern Territory and northwestern Queensland (Fig. 1). The Kombolgie underlies and forms the Arnhem Land Plateau, a several hundred meter high, inaccessible, deeply dissected topographic province. During a visit to the uranium deposits of the region in June-July, 1977, the lower 150-200 m or so of the formation, consisting of conglomerate and sandstone, was studied at eight localities along the escarpment between Katherine in the south and East Alligator in the north, a distance of about 300 km (Fig. 1). Field work included the measurement of a representative stratigraphic column, the measurement of about 400 paleo-current indicators, the observation of sedimentary structures to assist in the determination of the environments of deposition, and the collection of numerous Kombolgie samples for laboratory study.

The Carpentarian (Upper Precambrian) Kombolgie Formation unconformably overlies the uranium-bearing Lower Proterozoic sequence (Fig. 2) of the Pine Creek Geosyncline in the Alligator Rivers uranium subprovince and the South Alligator River uranium subprovince, and may have extended as far west as the Rum Jungle uranium subprovince. The former subprovince includes the large and rich deposits at Jabiluka, Ranger, Koongarra and Nabarlek, and the latter two subprovinces contain numerous small deposits mined out in the 1940's, 1950's and 1960's. At Rum Jungle, the younger (<1400 m.y. old) Adelaidean Depot Creek Sandstone (Walpole, et al, 1968) may have overlain the uranium deposits with a similar unconformable relationship.

Figure 1. Location maps showing location of study area and of localities mentioned in text.

Figure 2. Diagrammatic representation of Kombolgie Formation unconformably overlying Lower Proterozoic rocks. Uranium ore bodies are shown at left.

In general, there are two opposing hypotheses on the origin of the uranium deposits--metamorphic-hydrothermal and supergene. According to the metamorphic-hydrothermal concept, syngenetic uranium in black shales of the Lower Proterozoic Koolpin and Cahill Formations (equivalents) was released and locally concentrated during metamorphism, later to be buried and preserved by the younger units, primarily the widespread Kombolgie Formation. Details of this hypothesis can be found, for example, in Dodson, et al (1974), Smart, et al (1975), and Hegge and Rowntree (1978).

According to the supergene concept, oxidizing surface or near-surface waters carrying uranium deposited it in chemically and structurally favorable sites. These waters may have been moving either through the regolith on the peneplained pre-Kombolgie surface, through

the regolith and unlithified Kombolgie sands during or after their deposition, or along the sub-Kombolgie unconformity after lithification. Variations of this concept have been put forth by Ayres and Eadington (1975), Langford (1977), and Kalliokoski, Langford and Ojakangas (1978). A third type of hypothesis, diagenetic hydrothermal has more recently been put forth for similar deposits in northern Saskatchewan, with the uranium derived from within the overlying Athabasca Formation and deposited at the subjacent unconformity where chemical and structural conditions were suitable (Hoeve, Sibbald and Ramaekers, 1979).

Determination of the directions of movement of such uranium-bearing surface or near-surface waters of the supergene model, and to a lesser degree of waters in a diagenetic hydrothermal model, would be of some value in ascertaining the sources of the uranium as well as possibly providing some regional guides for further extension of exploration models and concepts. Obviously, the determination of a hydrodynamic framework which operated 1500 m.y. ago is difficult. However, if it is assumed that these uranium-bearing waters were moving down the same regional paleoslope which controlled the sedimentation of the Kombolgie sandstones and conglomerates, then paleocurrent indicators in the lower Kombolgie rocks should provide this information. Furthermore, determination of the environment of deposition of the sandstone should be of value in helping to evaluate the viability of the supergene concept; if a marine environment is indicated, the hydrologic framework would probably be unsuitable for the formation of supergene deposits. It was for these reasons that this limited sedimentological study of the conglomerate and sandstone of the lower part of the Kombolgie Formation was undertaken.

Stratigraphy and General Lithology

The Kombolgie Formation is 500-600 m thick, consisting of a lower conglomerate-sandstone member as much as 300 m thick, a middle volcanic member (the Birdie Creek and Nungbalgarri Volcanics) and an upper sandstone member as much as 200 m thick (Smart, et al, 1975). This study is concerned with only the lower 150 to 200 meters or so of the formation, the portion which was readily accessible along the west-facing erosional escarpment which marks the edge of the Arnhem Land Plateau (Fig. 3) and in nearby erosional outliers (Fig. 4). The Kombolgie rests unconformably upon Lower Proterozoic rocks (Figs. 2 and 5) which recently have been designated the Cahill Formation (Needham and Stuart-Smith, 1976) in the northern part of the area of study, and upon the 1740 m.y. old Edith River Volcanics in the south (Walpole, et al, 1968).

A thin zone of quartz- and quartzite-rich, hematitic, somewhat reworked "regolith" (?) termed HQB or hematite-quartz breccia locally marks the contact between the Lower Proterozoic and the Kombolgie; this "regolith" consists of a mixture of angular pebbles of quartz and quartzite (probably recrystallized vein quartz or recrystallized chert, rather than true metaquartzite), and sub-rounded quartz sand set in a fine hematite-clay matrix (Fig. 6). The angularity of the pebbles which would have become rounded by only a few kilometers of transport, indicates that this rock type is in part a residual or only slightly reworked accumulation. In the Rum Jungle and South Alligator River uranium subprovinces, the regolith is better developed than in the Alligator Rivers subprovince.

The basal part (a few tens of meters) of the Kombolgie is conglomeratic (Fig. 7) with rounded clasts as large as 30 cm in diameter. Most clasts are vein quartz, micaceous quartzite, and quartz-muscovite schist.

The conglomeratic rocks pass upward into a thick sequence of buff to reddish cross-bedded (Fig. 8) and plane bedded (horizontally laminated) quartzose sandstones (Fig. 9). Beds of red argillite a few inches thick are extremely rare. A generalized measured column from one locality is shown in Figure 10. Unfortunately, time did not permit the lateral tracing of units to observe the presence of lenticularity of beds and units, but no obvious lensing was observed.

Figure 3. Arnhem Land Escarpment just east of Koongarra.
View is to east.

Figure 4. Arnhem Land Escarpment at right distance and Mt. Brockman outlier at left. View is to the northeast from Nourlangie Rock.

Figure 5. Unconformity exposed near Koongarra on Mt. Brockman outlier. Man is standing on folded Lower Proterozoic schists and pointing at the contact. Subhorizontal Kombolgie Formation is at top of photo.

Figure 6A. Closeup view of basal conglomerate ("regolith") at same location as Figure 5. Lower Proterozoic is at bottom of photo.

Figure 6B. Photomicrograph of matrix of "regolith" shown in Figure 6A. Note large angular quartz pebbles and smaller rounded quartz sand. Dark area includes some pore space, clay and hematite. Field of view is 6 mm across. Crossed nicols.

Figure 7A. Cross-bedded conglomerate in lower part of formation at escarpment east of Koongarra.

Figure 7B. Cross-bedded conglomerate in lower part of formation at escarpment east of Koongarra.

Figure 8A. Large-scale planar cross bedding at escarpment east of Koongarra.

Figure 8B. Smaller scale planar cross-bedding at escarpment east of Koongarra. Note some trough cross-bedding at base.

Figure 9. Parallel (horizontal) bedding near Koongarra.

*Footage data for placement of unit 7 within the sandstones comprising units 6 and 8 were lost so placement is approximate.

Figure 10. Measured column in lower Kombolgie Formation on Mt. Brockman outlier west of Koongarra. Note braided stream facies (after Miall, 1977a); see Environment of Deposition section of this manuscript for explanation.

Sedimentary Structures and Textures

Cross bedding is common in the Kombolgie. Planar cross bedding (Fig. 8), usually with tabular sets, is the most abundant type. Trough cross beds (Fig. 11) are of lesser importance. Whereas the trough cross beds are usually small (most troughs are less than 100 cm wide and less than 15 cm deep), the planar cross-bed sets display a great variation in size. The thicknesses of 332 measured cross-bed sets, mainly of the planar type, are as follows: less than 25 cm = 42.7 per cent; 25-50 cm = 23.2 percent; 50-100 cm = 13.3 percent; 100-250 cm = 19 percent; and more than 250 cm = 1.8 percent, with two of the latter sets an estimated 10 meters thick. The average angle of dip of the cross-beds, after rotation of the formation tilt (5 to 50 degrees depending upon locality, but usually less than 20°) back to horizontal (an excessive rotation, for some initial dip is to be expected), is 16.7 degrees for a total sample of 328 foreset beds. Three samples of herringbone cross beds, with diametrically opposed dip directions in juxtaposed beds, were observed, one at Koongarra and two at Katherine (Fig. 12).

Plane bedding (horizontal lamination) is common and especially so in certain intervals (Fig. 9). Ripple marks (Fig. 13) are most common at Koongarra on Mt. Brockman; the majority of these are symmetrical, with ripple indices (wave length over amplitude) of 5 to 6, indicative of deposition in water (Reineck and Singh, 1975). Parting lineation, the result of the alignment of grains during rapid flow, was observed at half of the studied localities. Mudcracks (Fig. 14) were rarely observed.

Figure 11. Trough cross beds in unit 8 of measured column shown in Figure 10.

Figure 12. Herringbone cross beds in Katherine Gorge near Katherine.

Figure 13. Two types of ripple marks at Koongarra.

Figure 14. Rare mudcracks at Koongarra.

Pebble imbrication was noted in the lower conglomerate unit at Koongarra (Fig. 15). Scour channels were noted at the bases of conglomeratic units at several localities, with a maximum relief of 3 meters on a 10 meter wide channel (Fig. 16). There is a general fining-upward texture within some of the conglomeratic units, as at Koongarra (see Figure 10). However, such a textural change is lacking in most conglomeratic units and if a fining upward texture is present in the sandstones, it is not obvious in the outcrops.

The pebble-and cobble-sized clasts in the regolith and the basal conglomerate are angular to sub-rounded (Fig. 15) implying relatively little transport and abrasion, whereas pebbles in higher units are well-rounded (Fig. 17).

Detailed size analyses were not attempted; however, in most of the studied thin sections of sandstones, the grains are less than one millimeter in diameter, and commonly less than 0.5 millimeters in diameter.

Figure 15. Imbricated pebbles of angular vein quartz 10 m above the unconformity at base of the formation.

Figure 16. Part of conglomerate-filled channel cut into sandstones. Conglomerate is 3 m thick and 10 m wide.

Figure 17. Rounded pebbles, mostly quartz with some schistose quartzite, in lower part of formation at the escarpment east of Koongarra.

Environment of Deposition

Several characteristics of the lower Kombolgie Formation suggest deposition in a braided alluvial plain environment rather than in a network of meandering rivers. These include the general coarseness of grain size, the wide sheet-like expanse of the sandstone and conglomerate, and the abundance of planar cross-beds (e.g., Miall, 1977a, p. 30). The apparent lack of fining-upward sequences, the nearly total absence of fine-grained (clay and silt) beds and clay chips, and the rarity of mudcracks virtually eliminate a meandering channel-floodplain environment from consideration. Most of the fines apparently were carried on through the system.

The abundance of horizontal bedding in coarse sediments, the presence of lineation and conglomeratic detritus, indicate high velocity currents, at least partly in upper flow regime conditions (see Reineck and Singh, 1975, p. 107). Relative large scale cross-beds also suggest moderately high current velocities. The presence, especially at Koon-garra, of abundant ripple marks is compatible with a shallow water braided fluvial interpretation.

The few herringbone cross beds could be interpreted as the result of a tidal influence, but this appears to be incongruous with the total picture; they can be attributed to complexities of currents over and between bars. Some cross-bed sets many meters thick may be indicative of local aeolian activity, although the scale itself is not indicative; Coleman (1969) has reported bedforms with 15 m amplitude in channels of the Brahmaputra River. Unfortunately, such large, cross-bed sets in

the Kombolgie were generally observed on inaccessible cliff faces so further observations were not possible. The commonly unimodal paleo-current plots support a fluvial origin, as does the relatively steep (16.7°) angle of dip of the foreset beds.

All of the bed types can be related to deposition (accretion) on sand or gravel bars. The coarse planar (horizontal) beds are common on longitudinal (planar or massive) bars (e.g., Miall, 1977a, p. 1.10), whereas finer grained sandy beds may be flood deposits. The planar cross sets with tabular cross-beds are commonly formed by migrating large-scale ripples on linguoid (curved) and transverse (straight) simple foreset bars (e.g., Miall, 1977a, p. 1.12). The trough cross sets were probably formed by dune migration. Ripple marks are commonly low energy bar-top deposits or waning flood deposits; in either case, they represent breaks in sedimentation.

Several workers have noted that longitudinal bars are formed in more proximal braided stream systems whereas transverse or linguoid bars are formed further downstream (e.g., Eriksson, 1978; Boothroyd and Nummedal, 1978). While the lower and coarser part of the studied Kombolgie may contain longitudinal bar sediments, deposited nearer the source, the higher parts of the studied sequence appear to have been deposited in a slightly more distal location.

Several workers on braided stream deposits have developed depositional facies models. Miall (1977b; 1978) erected six vertical profile

models based on various assemblages of 10 facies types and Rust (1978) described six similar braided systems. This author was not aware of these works at the time of data collection, but a reconstruction from field notes, photographs and memory allowed a tentative generalized assignment of facies to the one measured column (see Fig. 10). The Kombolgie resembles Miall's Platte type or Rust's S_1 facies assemblage of proximal braided rivers and alluvial plains. Cant's (1978) facies model for a moderate-sized sandy braided river consists of a random stacking of St (trough cross-bedded sand), Sp (planar cross-bedded sand) and Sh (horizontally bedded sand) facies, and is comparable. Miall's Platte type profile, with the above facies in addition to minor Sr (ripple cross laminated sand) and minor Gm (massive or crudely bedded gravel), plus the addition of minor Gt (trough cross-bedded gravel) and Gp (planar cross-bedded gravel) also fits the data; the Platte type model is characteristic of very shallow sandy braided river systems. In each of these models, however, scale appears to be a problem. The total lack of vegetation in the Precambrian appears to require an increase in scale in order to make models based on modern braided streams applicable.

The repeated conglomerate of the measured column, and similar conglomerate units elsewhere in the Kombolgie, may indicate alluvial fan facies prograding basinward over the more common braided alluvial fan complex, perhaps the result of uplift in the source area, subsidence of the basin, or just the lateral migration of primary channels with higher velocities.

Coarse conglomerates with abundant sandstone clasts in the lower part of the Kombolgie at El Sherana are massive and poorly sorted, suggestive of debris flows (Fig. 18). These are apparently unique to this one locality.

It must be emphasized that this study encompasses what is essentially a quick two-dimensional look along one north-south traverse across the depositional basin. More detailed work is surely necessary to refine these general interpretations.

Figure 18. Unsorted conglomerate (debris flow?) low in the Kombolgie formation at El Sherana. Note that bedded sandstone clasts make up the bulk of the unit. Petrographic study indicates the clasts are very similar to the Kombolgie and were probably derived from the formation itself.

Paleocurrent Analysis

Approximately 400 paleocurrent measurements were made in the Kombolgie Formation at nine localities spread out along a distance of 250 kilometers (Fig. 19). Most of the measurements on the rose diagrams are based on cross-beds, but some parting lineations and asymmetrical ripple marks are also included. With the exception of the Koongarra area, where abundant ripple marks have a random distribution, the ripple marks and parting lineations fit the cross-bedding trend.

There is a strong trend in the paleocurrent pattern from the west and northwest towards the east and southeast, although there is a considerable spread and divergence of readings at Jabiluka, El Sherana, and Sleisbeck. At Sleisbeck, the trend in the sandstones above the Birdie Creek Volcanics shows a slight shift to the southwest from the more westerly trend beneath the volcanic unit. The paleocurrent plots at these latter three localities may indicate either the effects of local highs (sources) within the depositional basin or the lateral accretion on edges of sandbars. More field work is needed to better evaluate these possibilities.

Figure 19. Map showing paleocurrent patterns in the Carpentarian (Middle Proterozoic) lower Kombolgie Formation at various localities and at one locality of Adelaidean (Upper Proterozoic) Depot Creek Sandstone. All readings have been corrected for dip. Rose diagrams are compass plots, with north to the top. The number beside each plot signifies the number of cross-bed measurements.

Petrography

The majority of the pebbles in the conglomerates at most studied localities consist largely of vein quartz, micaceous quartzite, and quartz-muscovite schist, all resistant lithologies in the underlying Lower Proterozoic basement. At El Sherana, however, clasts of rhyolitic welded tuff and sandstone are abundant (Fig. 18) and at Sleisbeck rhyolite clasts from the underlying Edith River Volcanics are present. The quartzose sandy matrix of the conglomerates is essentially identical to the sandstone described in the following paragraphs.

The Kombolgie sandstones are mineralogically quite mature with quartz generally constituting more than 95 percent of the framework grains. Most quartz grains are unit common quartz grains, but stretched metamorphic quartz is commonly present (Fig. 20). Feldspar was observed in only a few thin sections, and then in only trace amounts; staining of thin section heels for K-feldspar verified this paucity. The sandstones of the three southern localities (El Sherana, Sleisbeck and Katherine), while still relatively mature mineralogically, contain chert and rhyolite framework grains in small amounts (Fig. 21).

Texturally the sandstones are submature to mature. Whereas many samples consist of well-rounded and well-sorted quartz grains cemented by silica (Fig. 20), a majority are more poorly rounded and more poorly sorted, with a sericitic clayey matrix (Fig. 22).

The non-opaque heavy mineral residues from 18 sandstone samples consist of a stable suite of rounded zircon and tourmaline; rutile is minor. Hematite and leucoxene are the major opaque heavy minerals.

Major diagenesis includes the recrystallization of the clayey matrix to sericite, and silica cementation. Diagenetic crystalline diaspore is abundant in basal Kombolgie sandstone which rests upon granite near Jabiluka; this is suggestive of an intensive weathering and a possible kaolinite predecessor. Tourmaline heavy mineral grains commonly show the results of extensive intrastratal solution but when this occurred is impossible to ascertain.

Figure 20. Photomicrograph of Kombolgie sandstone from Koongarra. Note abundance of well-rounded unit quartz grains and silica cement and presence of some stretched metamorphic quartz grains. Field of view is 3 mm across. Crossed nicols.

Figure 21. Photomicrograph of Kombolgie sandstone from El Sherana. Note presence of rounded chert grains and silica cement. Kaolinitic clay occupies some of the interstices. Field of view is 3 mm across. Crossed nicols.

Figure 22. Photomicrograph of Kombolgie sandstone from escarpment east of Koongarra. Note unit quartz grains and silica cement. Both Kaolinitic and sericitic clay fill the interstices. Field of view is 3 mm across. Crossed nicols.

Sedimentation

Environmental indicators support the interpretation of deposition of the sand-dominated lower Kombolgie sequence in a vertically aggrading braided alluvial plain environment in which both downstream and lateral migration of bars formed widespread sand sheets. The great total thickness of sandstones and associated conglomerates (500 m) in the entire Formation suggests that the basin in which the Kombolgie was deposited was located adjacent to a tectonically active source area from which periodic floods or surges transported abundant loose sediment to the aggradational site. Appreciable concomitant subsidence of the depocenter seems likely in order to attain the total thickness of the formation, but may not have been necessary if adjacent relief was sufficient. The deposystem apparently encompasses the entire MacArthur Basin, so regional studies will be necessary in order to ascertain the larger depositional setting. Braided systems generally develop on relatively steep proximal slopes, as opposed to meandering channels and flood plains (Leopold and Wolman, 1957). Obviously the Kombolgie once extended far to the west (tens to hundreds of kilometers) of its present western margin at the escarpment.

Since the paleocurrent patterns in general suggest a dominance of westerly and northwesterly sources, the sediments comprising the since-removed Kombolgie to the west were likely coarser, as a whole, than those studied here, and thicker as well. While it is certainly possible that the paleocurrents do not point back towards a general source region to the west and northwest, for river systems can flow parallel to

tectonically uplifted lands (e.g., Miall, 1977a, p. 33), the similarity in the paleocurrent patterns in the Koongarra and Katherine areas, which are widely separated and from which many readings were taken, suggests a wide fluvial system, probably the result of a major uplifted tectonic feature situated to the west-northwest. Some support for multiple sources is provided by less mature detritus at El Sherana and Sleisbeck where paleocurrents also diverge from the apparent norm.

The since-eroded western Kombolgie sediments, lithologic and temporal equivalents of the Kombolgie braided alluvial plain system described here, probably comprised piedmont alluvial fans. Thus the total piedmont alluvial fan-braided alluvial plain system could have covered as much as $250,000 \text{ km}^2$, certainly a large area but comparable to the modern molasse depocenter south of the Himalayas. There are many analogs of comparable size in the geologic record, including the Cretaceous of western North America.

Long (1978) listed several thick Proterozoic sandstone units which have been interpreted as being of braided fluvial origin. Of these, the Athabasca Formation of northern Saskatchewan (Ramaekers and Dunn, 1976) is of greatest interest here; it covers a comparable area, it both overlies and contains pitchblende deposits which are related to the underlying unconformity, and in many ways is similar to the Kombolgie.

The total lack of vegetation during Late Precambrian time would have enhanced erosion and hence sedimentation rates, as emphasized by, e.g., Schumm (1969) and Long (1978), and would logically have been a

major factor in the establishment of a braided alluvial plain environment.

The source rocks for the Kombolgie detritus were probably Archean and Lower Proterozoic plutonic and metamorphic rocks. An orogenic-magmatic event occurred in northern Australia about 1800 m.y. ago based on radiometric ages of several granites to the west of the Kombolgie (Walpole, et al, 1968). This event may well have raised the source areas; subsequent erosion over the succeeding 100-300 m.y. or so may have also exposed the granitic plutons, making them possible sources as well.

Significance to the Origin of the Uranium

Deposits of the Northern Territory

The unconformity-related Proterozoic pitchblende deposits of the northern end of the Northern Territory may have had a metamorphic-hydrothermal origin at about 1800 m.y. ago, mobilized from syngenetic uranium in 2200 m.y. old black shales, as argued forcefully by Dodson, et al (1974), Smart, et al (1975), and Hegge & Rowntree (1978). If so, the Kombolgie is post-ore in age and has simply served the function of a good caprock which prevented erosion and/or dissolution of the ore deposits. If, however, the ore deposits had a younger supergene origin as proposed by Ayres and Eadington (1975), Langford (1977), and Kalliokoski, Langford and Ojakangas (1978), surface and near-surface waters may have deposited the uranium in the Lower Proterozoic rocks at sites with favorable chemical (i.e., reducing) and structural (i.e., space) characteristics. In this hypothesis, the deposition of the Kombolgie Formation, and especially the lower Kombolgie, assumes a central importance in the epigenetic picture.

The waters which might have carried the uranium out of the same source rocks which supplied the pebbles, sand and clay to the Kombolgie depocenter, would have been oxidizing waters less than 1800 m.y. old. As put forth by Kalliokoski and others (1978), these waters may have (1) flowed across the peneplaned surface over and in the regolith prior to deposition of the Kombolgie clastics or (2) may have been the same waters which carried the clastics, or (3) may have moved through the unconsolidated Kombolgie clastics and the underlying regolith.

It is also theoretically possible that the waters may have moved through the regolith and the Kombolgie after initial lithification but before final diagenesis minimized the porosity and permeability. In any case, the only way to determine the flow direction of these waters which would probably have moved sometimes between 1800-1400 m.y. ago was to analyze the depositional framework of the lower Kombolgie conglomerates and sandstones. Now that this has been done, it can be stated that most of the waters flowed towards the east and southeast down the dominant paleo-slope which provided the major impetus for the hydrologic gradient. This finding provides an additional reason to suspect the presence of other unconformity-related pitchblende vein deposits, similar to Jabiluka Two (e.g., Hegge and Rowntree, 1978), beneath the Kombolgie Formation.

Using this model, the uranium carried in solution was probably derived from the plutonic and metamorphic rocks of the same source area that provided the pebbles, sand and clay. Not many data are available on these weathered western source rocks, for their remnants are buried beneath a Mesozoic and Cenozoic cover. Logically, they included some Archean rocks, the Lower Kombolgie metasediments and the 1800 m.y. old granites which intruded them. Their uranium content is not critical, for it is generally accepted that a source rock with only a few ppm uranium can, over a long period of time, supply sufficient uranium for an ore deposit.

It has been suggested by many workers that the leachable uranium of granitic rocks is largely in intergranular spaces as thin films. Therefore, the Kombolgie detritus itself would have been a source for leachable uranium prior to final cementation. Similarly, uranium

adsorbed to clay particles and deposited as clayey matrix within the Kombolgie may have been leached in situ. The Kombolgie sands appear to be quite barren now, but this assertion is based only on scintillometer readings on surface exposures that are likely not representative of fresh rock. The implication here is that even the Kombolgie sediments could have supplied uranium via lateral and downward percolation of oxidizing waters until the reducing chemical environments of the calcareous-pyritic-graphitic Lower Proterozoic rocks were encountered in structurally prepared spaces such as fault zones or leached-collapsed carbonate beds. Unfortunately, even chemical analyses of the Kombolgie and of the feldspars and clays therein may not test this hypothesis, for low uranium contents could be ascribed to either a lack of initial uranium or in-situ leaching. Comparisons of the uranium contents of the sands and clays with those of relatively fresh pebbles in the conglomerate would at least reveal whether or not leaching had occurred, but would not indicate whether the leaching occurred during weathering prior to erosion and sedimentation, or after deposition. Some chemical studies are currently in progress.

Conclusions

This investigation has provided additional information about the possible source rocks, has shown the major transport direction of the currents that carried the detritus and that may have carried dissolved uranium, and adds further support to the thesis that other uranium deposits are quite probably present along the unconformity beneath the Kombolgie Formation.

Sedimentological studies of the overlying caprock can be of value in modeling the origins of unconformity-related pitchblende vein deposits. Unfortunately, like several other modes of attack, they provide additional data for the models but seldom yield unique solutions.

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