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The Genesis of Proterozoic Uranium Deposits in Australia

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The genesis of Proterozoic uranium deposits in Australia

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The principal mineral deposits of Proterozoic age in Australia, not only of uranium but also of base and precious metals, are found within a north-trending belt central to the continent which stretches from Adelaide to Darwin.

This belt represents the margin to the West Australian Archaean craton, and comprises orogenic and shelf domains that evolved throughout the Proterozoic; and it is suggested that the formation of the uranium deposits was an integral part of the evolution of the various geosynclines in the belt.

The uranium ore bodies occupy structurally prepared features such as shears, faults and breccias, and are clearly introduced, but the source of the mineralizing fluids, and the precise mechanism of deposition, is, in some cases at least, in dispute.

Mineralization *per ascensum* by connate water carrying metals desorbed from the sedimentary pile, or in association with acid magma which may itself be the product of anatexis, is favoured by the author.

Introduction

Stratigraphy

The Precambrian in Australia has been divided into four, of which the upper three are assigned to the Proterozoic and the lowest to the Archaean (Fisher & Warren 1975). Nomenclature and approximate ages are given below:

Upper Proterozoic	1400–600 Ma	Adelaidean
Middle Proterozoic	1800–1400 Ma	Carpentarian
Lower Proterozoic	2200–1800 Ma	Nullaginian
Archaean	+2200 Ma	

The grand unconformity at the base of the Mt Bruce Supergroup in Western Australia marks the bottom of the Proterozoic, although the age limit of 2200 Ma is somewhat uncertain.

Important metamorphic and orogenic events are recorded in most of the Proterozoic provinces at around 1800 Ma, which serves as a suitable division between Lower and Middle Proterozoic. The classical Adelaidean succession of South Australia is the type area for rocks of that age, and stands as a worldwide standard thanks to the superb exposures in the Adelaide Geosyncline.

The type Nullaginian succession is that of the Mt Bruce Supergroup in the Hamersley Province of northwestern Australia where there is a very thick accumulation of shelf sediments. They exhibit the classic cycle, which is discernible throughout most of the Proterozoic, from a lower group of coarser clastics and volcanics, through a middle group in which pelites and chemical sediments predominate, to an upper group which exhibits a return to more active sedimentation and the deposition of coarser detritus, with or without igneous activity.

In the lower Proterozoic Pine Creek Geosyncline of north Australia a lower succession comprising arkose, sandstone, greywacke and dolomite with few pelitic and chemical members

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passes upwards into a middle sequence of pelitic rocks with a marked chemical component. An upper sequence of medium grained detrital sediments lacks chemical sediments (Eupene, Fraser & Ryan 1976).

Although the metamorphic grades are considerably higher, a similar pattern is discernible in the Gawler Block in South Australia, also of Nullaginian age, where the quartzo-felspathic Flinders Group is succeeded by the Hutchinson Group and its correlative, the Middleback Group, in which iron formation is prominent (Johns 1961), and which is correlated with the Mt Bruce Supergroup. Nullaginian successions are also present in the Musgrave, Arunta, and Tennant Creek Blocks and in the Birrindudu Basin (figure 1). The Halls Creek Group in the Halls Creek Mobile Belt (Dow & Gemuts 1969) may be somewhat older.

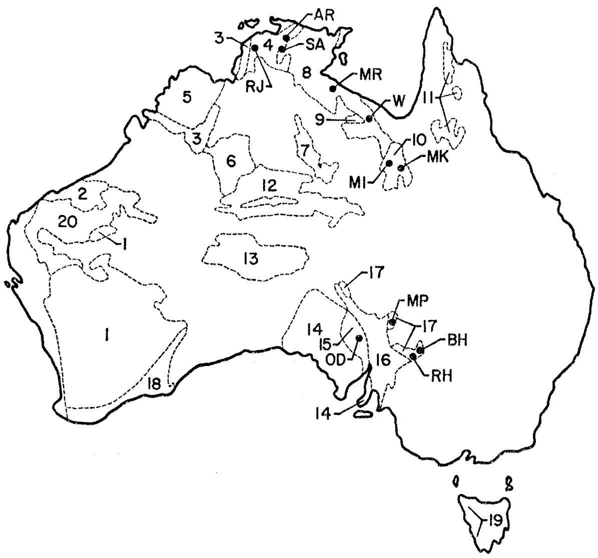

FIGURE 1. Precambrian tectonic units of Australia, showing the location of some of the more important Proterozoic ore deposits. (A), Archaean; (P_l, P_m, P_u), Lower, Middle and Upper Proterozoic respectively. 1, Yilgarn Block (A); 2, Pilbara Block (A); 3, Mobile Belts (A–P); 4, Pine Creek Geosyncline (P_l); 5, Kimberley Basin (P_l); 6, Birrindudu Basin (A–P); 7, Tennant Creek Block (P_l); 8, McArthur Basin (P_m–P_u); 9, Murphy Tectonic Ridge (P_l); 10, NW Queensland Orogenic Province (P_l–P_u); 11, N Queensland Inliers (P_l–P_m); 12, Arunta Block (P_l–P_m); 13, Musgrave Block (P_l–P_u); 14, Gawler Block (A–P_m); 15, Stuart Shelf (P_u); 16, Adelaide Geosyncline (P_u–P); 17, Willyama, Mt Painter, Peake–Denison Inliers (P_l); 18, Fraser Range Province (P_m); 19, Tasmanian Province (P_u); 20, Hamersley Province (P_l–P_m). AR, Alligator Rivers Province; MK, Mary Kathleen; MP, Mount Painter; BH, Broken Hill; RJ, Rum Jungle; MI, Mount Isa; SA, South Alligator; W, Westmoreland. OD, Olympic Dam; RH, Radium Hill; MR, McArthur River.

Middle Proterozoic rocks have their best development in a belt stretching along the Gulf of Carpentaria from the Pine Creek Geosyncline to the Northwest Queensland Orogenic Province (figure 1). The geology of the region has been well summarized by Plumb & Derrick (1975). The sediments of the McArthur Basin are moderately folded but extensively faulted, notably along the meridional Batten Trough, which separates attenuated shelf sequences to east and west. The lowermost Tawallah Group consists of coarser-grained clastic sediments and volcanics with, at its base, the Westmoreland Conglomerate, which is host to the Westmoreland uranium deposits. In the northwest the Katherine River Group correlates with the Tawallah Group. At its base lies the Kombolgie Formation, and locally the Edith River Volcanics, which immediately overlies the eastern part of Pine Creek Geosyncline.

The MacArthur Group overlies the Tawallah Group, and consists principally of siltstone, shale, dolomite, with chert, claystone, sandstone and tuff, and above that lies the Roper Group, which consists of quartz, sandstone, with ferruginous members, micaceous siltstone and shale.

The Murphy Tectonic Ridge separates the MacArthur Basin from the Northwest Queensland Orogenic Province (figure 1), where orogenesis has been more severe. Nevertheless, correlations can be made across the ridge. A north-trending crystalline ridge occupies the centre of the province, splitting it into two troughs. Mount Isa lies in the western trough, in the Mount Isa Group, and Mary Kathleen in the eastern trough, in the Mary Kathleen Group. These two groups are correlatable with, and lithologically comparable to, the MacArthur Group.

The Haslingden Group, which lies below the Mount Isa Group, correlates with the Tawallah Group and includes the Eastern Creek Volcanics, host to a number of small uranium ore bodies.

In southern Australia the Carpentarian is marked by widespread igneous activity which gave rise to the Gawler Range Volcanics (Thomson 1975*a*).

The Adelaidean is best represented in the Adelaide Geosyncline, and strata of this age extend northwards into the Amadeus Basin between the Musgrave and Arunta blocks. They are moderately to strongly folded, and diapirism is common. In northern Australia the Adelaidean is represented by gently folded shelf sediments that are present in many places, and by basic intrusion on a large scale in the Musgrave Block (Thomson 1975*b*). Uranium is present at or near the base of the Adelaidean at Mount Painter and Olympic Dam.

Tectonic outline

Fisher & Warren (1975) have outlined the tectonic evolution of Australia. In broad terms the record shows the gradual eastwards accretion of the Australian continent in Proterozoic times, with shelf sedimentation to the west and deeper water sedimentation and orogenesis further east.

Thus the Nullaginian sediments of the Hamersley Province and the Kimberley Basin are for the most part gently disturbed, whereas their correlatives in northern, central and southern Australia are generally severely folded and metamorphosed, commonly to granulite facies.

The Middle Proterozoic strata of the Northwest Queensland Orogenic Province were involved in an orogenic event that left the MacArthur Basin to the northwest relatively untouched, though faulting there is common. The Gawler Block was stable during the Carpentarian.

The Adelaidean platform sediments of South and Central Australia were folded, faulted and locally overthrust by early Palaeozoic events that impinged on the older Proterozoic shield. In South Australia the Adelaide Geosyncline, which trends north, separates the Gawler Block from a nucleus of rocks of comparable age, the Curnamona Nucleus, which crop out in the Willyama Inlier and other exposures (Thomson 1975*c*). In central Australia an east-trending Palaeozoic orogeny was imposed on the older Proterozoic of the Musgrave and Arunta Blocks, creating the Amadeus Basin in between. The Giles Complex in the Musgrave Block represents early Adelaidean igneous activity on a scale unknown elsewhere in the latter part of the Proterozoic.

Mineralization

Thomson (1973) has pointed out that uranium, copper, and silver–lead–zinc mineralization in the Australian Proterozoic is overwhelmingly concentrated in a meridional belt that is bounded roughly by Rum Jungle, Mary Kathleen, Broken Hill and the Gawler Block (figure 1).

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Virtually all of the Proterozoic uranium deposits fall within this belt, as do Mount Isa, McArthur River, Broken Hill, Wallaroo and Moonta, Tennant Creek, Mount Gunson, and the newly discovered Cu–U deposit at Olympic Dam in South Australia. He relates this phenomenon to the presence of fundamental north-trending lineaments that are apparent in the mid-ocean ridge to the south of the continent.

Lower Proterozoic orogenesis is rare to the west of this zone and anatexis is virtually absent; but in the two units where it does occur, the Wyloo Group and the Halls Creek Group, uranium and base metal mineralization is known, though on a small scale. It is the author's belief that two factors account for the localization of mineralization within the belt. On the one hand profound faulting has created troughs for sea-floor sulphide accumulation, and the channels to feed these troughs. On the other, orogenesis and the accompanying anatexis has liberated metals from the sediment piles, with subsequent deposition in suitable structural traps at higher stratigraphic levels.

The prolonged period of exposure of the continent has caused a substantial amount of redistribution of minerals at the surface, particularly where uranium is concerned.

The uranium deposits

The principal uranium deposits of the Proterozoic have been described recently by Ryan (1977). The Pine Creek Geosyncline is of overwhelming importance, as the host to the orebodies of Rum Jungle, the South Alligator Valley, and the Alligator Rivers districts as well as a number of other small bodies. In previous years ore was won from the Whites, Dysons, Rum Jungle Creek South, and Mount Burton orebodies at Rum Jungle, with reserves extant at Mount Fitch. El Sherana, Palette, Coronation Hill, Rockhole and Sleisbeck were the principal producers in the South Alligator Valley, though all were small.

Jabiluka and Ranger One, in the Alligator Rivers District, together contain more than 300000 t of uranium oxide, and remain unclosed at depth in each case, with Koongarra, Nabarlek and a number of smaller deposits spread throughout the district. In the Westmoreland area the Eva Mine produced small tonnages of ore, and there are undeveloped orebodies at Cobar II, El Hussen, Redtree, Old Parr, and Longpocket.

Mary Kathleen, Australia's only producing mine, is the most prominent of the Northwest Queensland Province, with mineable deposits at Skal, Valhalla, and Andersons Lode in the Eastern Creek Volcanics, together with a host of other prospects.

The oldest producer in Australia is Radium Hill, in the Willyama Complex in South Australia. Other South Australian deposits are Crocker Well, Mount Painter, and Olympic Dam.

All of the deposits of the Pine Creek Geosyncline, with the exception of the ABC, are in the Lower Proterozoic, or, locally, at the base of the overlying Carpentarian strata. The Westmoreland and Mount Isa deposits are, on the other hand, all in the Middle Proterozoic, with the exception of the Eva Mine, which occurs in Nullaginian rocks just below the unconformity.

In South Australia, Radium Hill and Crocker Well occur in Nullaginian metamorphics; the Mount Painter bodies lie just above the unconformity at the base of the Adelaidean; and the Olympic Dam deposit appears to occupy the same position as Mount Painter.

Regional setting

The Pine Creek Geosyncline has been described in detail by Walpole, Crohn, Dunn & Randall (1968). At Rum Jungle all of the uranium bodies lie within a sequence of metapelites, which have been metamorphosed to greenschist facies, immediately overlying a thick dolomite formation, or locally, as at Mt Fitch, within the dolomite (Berkman 1968). The sediments form part of a near-shore shallow-water succession that is draped around an Archaean basement dome, the Rum Jungle Complex, and they lie along a faulted syncline formed between this dome and a similar one to the south (figure 2).

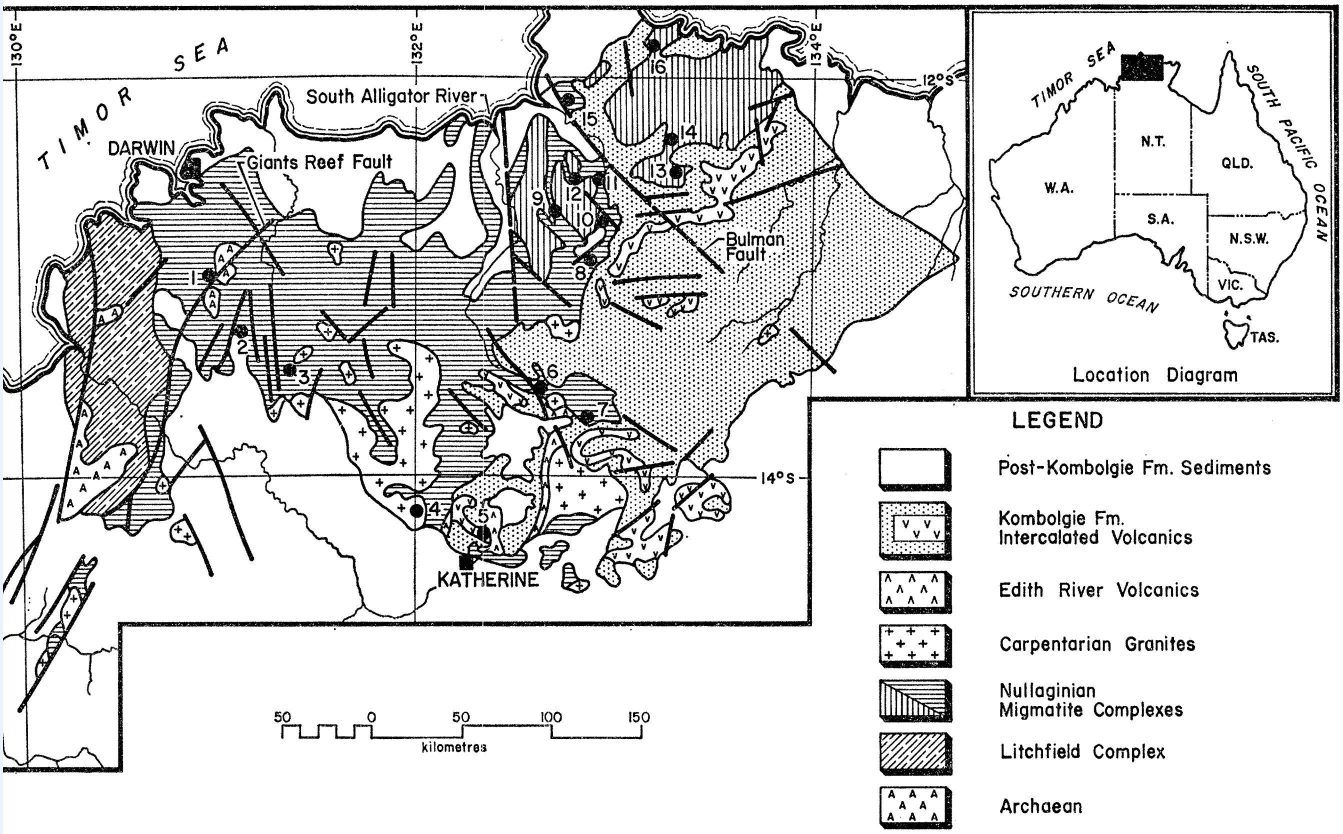

FIGURE 2. The geology of the Pine Creek Geosyncline, showing the location of uranium deposits. 1, Rum Jungle; 2, Adelaide River; 3, Fleur-de-Lys; 4, Edith River; 5, ABC; 6, S Alligator Valley; 7, Sleisbeck; 8, Koongarra; 9, Austatom One; 10, Ranger One; 11, Jabiluka; 12, Ranger Four; 13, Karamal; 14, Nabarlek; 15, Arrara; 16, Black Rock.

The South Alligator Valley deposits are located along a valley containing faulted Nullaginian metasediments that are overlain by generally flat-lying Carpentarian volcanics and sandstone. Uranium mineralization is localized along structural dislocations in ferruginous cherty siltstone adjoining carbonaceous shale; in the overlying sandstone where it is faulted against the pelitic rocks; and in some cases in overlying volcanic rocks. The regional relationships are obscured by younger cover to a great extent. A granite of Carpentarian age intrudes the Lower Proterozoic sequence towards the southern end of the valley (Taylor 1968).

The larger Alligator Rivers deposits lie along the eastern flank of, and just above the Nanambu migmatite complex which is very poorly exposed but is thought to consist of Archaean rocks with infolded migmatitized Nullaginian metasediments (Smart, Wilkes, Needham & Watchman 1975). Nabarlek lies on the western flank of a similar complex (the Nimbuwah Complex) further to the east (figure 2). A strongly folded synclinorium separates the two complexes. Metamorphism increases in grade from southwest to northeast.

At Koongarra, Ranger One and Jabiluka, the host rocks are quartz, chlorite, muscovite and graphitic schists, locally interbedded with magnesian carbonate rocks. Retrograde chlorite metamorphism has been imposed on an earlier amphibolite facies.

The Nullaginian metasediments have been intruded by post-deformational dolerite and phonolite, which may be comagmatic, and biotite granite which exhibits relatively high radioactivity. There are concordant, predeformation basic bodies that are believed to be sills.

The unconformity at the base of the overlying Kombolgie Formation, of Carpentarian age, is nowhere more than perhaps 200 m stratigraphically above the deposits, and locally it is much closer.

At Westmoreland there is minor uranium mineralization in the Nullaginian Cliffdale Volcanics at the Eva Mine, but most of the ore bodies are found in association with basic dykes emplaced along joints in the overlying Carpentarian Westmoreland Conglomerate, a correlative of the Kombolgie Formation (Hills & Thakur 1975). The Cliffdale Volcanics are moderately regionally metamorphosed and folded, but the Carpentarian strata are only gently warped. Volcanic rocks overlie the Westmoreland Conglomerate.

Regional metamorphism in the western trough of the Northwest Queensland Province is of generally very low grade, but the Eastern Creek Volcanics exhibit alteration that may be due to autometamorphism, to hydrothermal alteration, or to regional metamorphism (Carter, Brooks & Walker 1961). The formation includes substantial thicknesses of psammitic rocks that are the principal hosts to the uranium lodes.

Whereas the western trough is predominantly faulted, folding predominates in the eastern trough (Plumb & Derrick 1975). The Corella Formation is metamorphosed to hornblende hornfels grade by the Burstall Granite, which crops out about 3 km east of the Mary Kathleen orebody (Derrick 1977). The Mary Kathleen Group is more highly regionally metamorphosed, and scapolitization is widespread.

In South Australia the Lower Proterozoic metamorphic complexes of the Gawler Craton and Willyama, Mt Painter, and Peake–Denison Inliers (Thomson 1975*a*, *c*) comprise metasediments, migmatites, and intrusive rocks not stratigraphically dissimilar to those of the Pine Creek Geosyncline, but of a higher grade of regional metamorphism. Granulite facies is common, and where this grade has not been reached, amphibolite facies predominates. The stratigraphy around Radium Hill and Crocker Well in the Willyama Inlier is not well known, but further east at Broken Hill, Stanton (1976) has postulated the presence of downfaulted troughs, in which finer grained pelitic and chemical sediments collected, separated by horsts made up mainly of altered acid volcanics that have been metamorphosed to sillimanite gneiss. At Radium Hill the host rocks are paragneisses formed by granitization of pre-existing sediments (Whittle 1954*a*).

The host rocks at Mount Painter are now believed to be Adelaidean arkosic breccias, with tillitic affinities, that lie unconformably on the Mount Painter metamorphic complex (I. Youles, personal communication). As such, they represent the only known uranium orebodies

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of any importance so far discovered in the Adelaidean. The host rocks at Olympic Dam are described in a recent release by the South Australian Department of Mines (S.A.D.M. 1977) as 'granitic breccias'. They appear to lie at or near the base of the Adelaidean on the Stuart Shelf, and therefore may be comparable to the Mount Painter deposits.

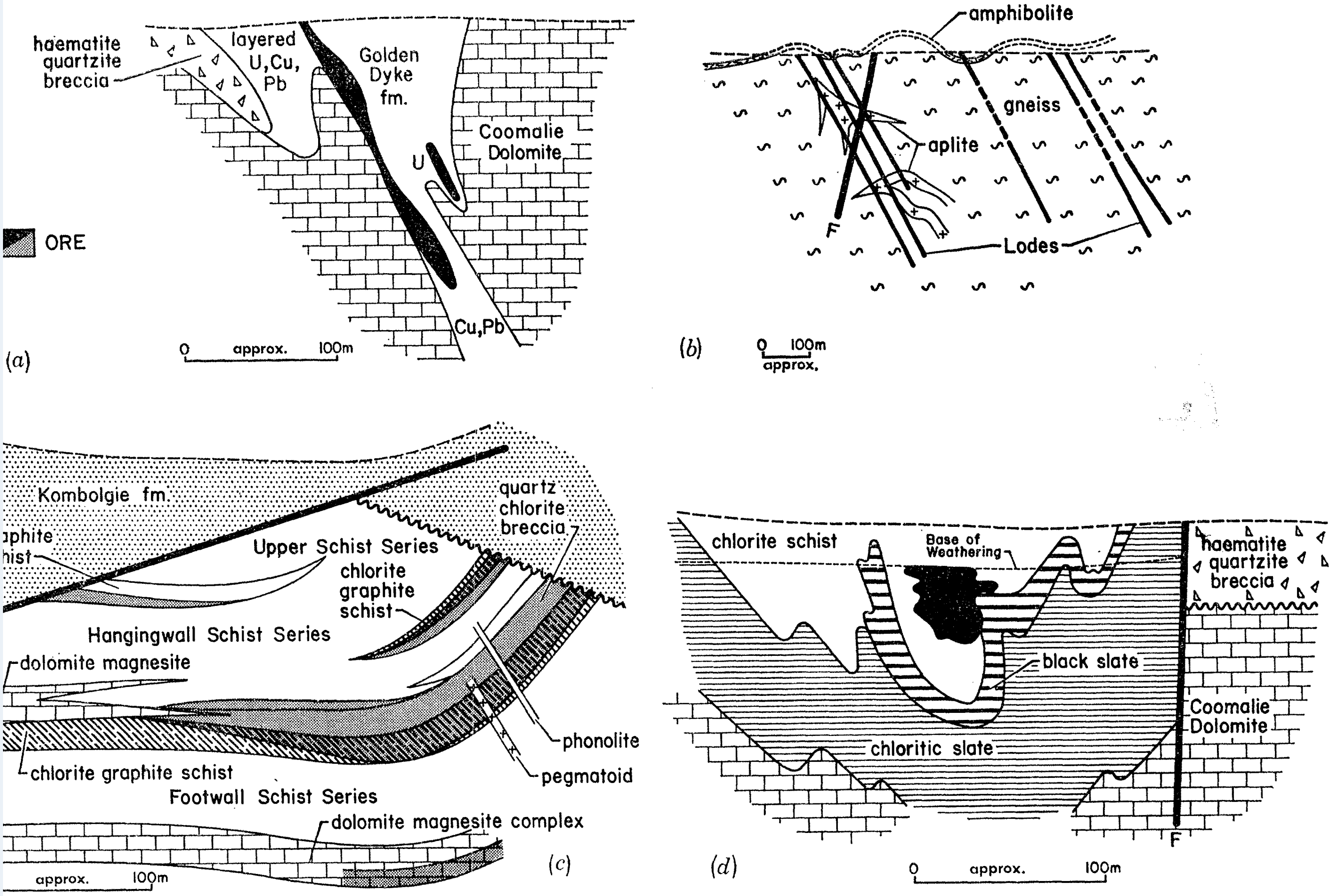

FIGURE 3. Diagrammatic cross sections of Australian uranium deposits. (*a*) Whites, Rum Jungle; (*b*) Radium Hill; (*c*) Jabiluka Two; (*d*) Rum Jungle Creek South.

Structural setting

Diagrammatic cross sections of a number of orebodies are shown in figures 3 and 4. At Rum Jungle, Whites and Dysons deposits occur in a complexly faulted and sheared syncline that has been faulted and folded into the western flank of the Rum Jungle Complex (figure 3*a*). The host rocks are sheared and brecciated, and mineralization has been located within these later structural features to some extent, but there is evidence of an earlier, probably syngenetic, disposition of stratabound mineralization which was subsequently remobilized by faulting and folding (Fraser 1975).

Taylor (1968) has noted that in every well documented uranium occurrence in the South Alligator Valley, 'primary ores are associated with faulting and shearing'.

In the Alligator Rivers Province, at Koongarra, the ore is present preferentially in tightly folded and brecciated metasediments (Foy & Pedersen 1975). At Ranger One Eupene, Fee & Colville (1975) have invoked solution and collapse of carbonate rocks to account for the structural preparation of the host rocks that is evident there (figure 4*e*). At No. 3 Orebody it appears that blocks of the Kombolgie Formation may have been incorporated in the collapse zones. The mineralization at Jabiluka is concentrated along the axis of a gentle syncline and is associated with brecciation of the host schists, and here, as at Ranger One, Rowntree & Mosher (1975) note that breccia zones containing chert equate stratigraphically with dolomite–magnesite sequences away from the orebodies (figure 3*c*). The Nabarlek orebody is emplaced on a shear that cuts obliquely across the grain of country rocks (Anthony 1975).

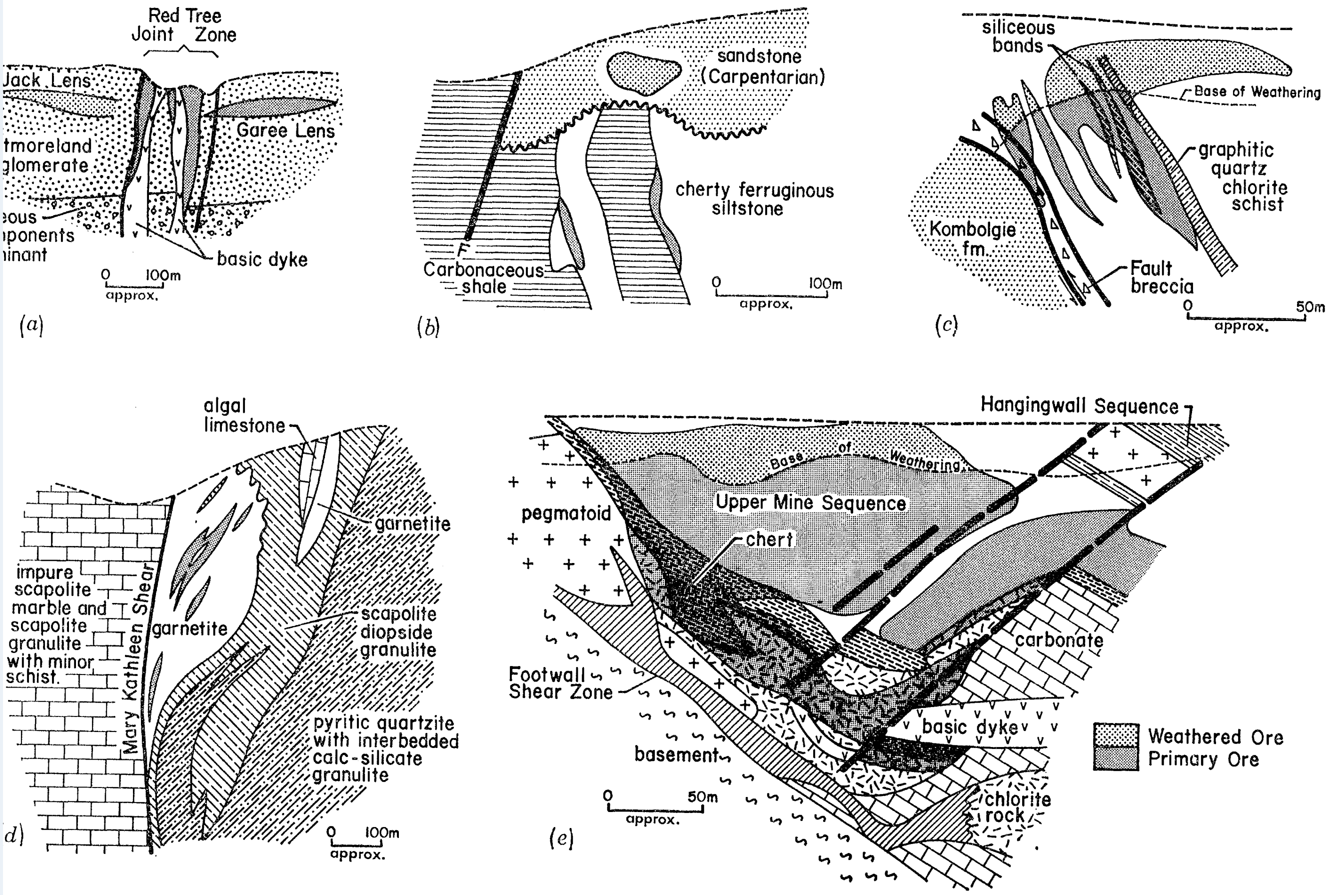

FIGURE 4. Diagrammatic cross sections of Australian uranium deposits. (*a*) Westmoreland; (*b*) South Alligator; (*c*) Koongarra; (*d*) Mary Kathleen; (*e*) Ranger One.

In the Westmoreland province, mineralization is associated with dykes emplaced along throughgoing joints that appear to be tension fractures associated with gentle warping of the Westmoreland Conglomerate (figure 4*a*). Interestingly, the Redbank copper deposits that lie to the north are found in collapse breccias that are concentrated along similar fractures (Orridge & Mason 1975). At the Eva Mine, the ore shoots occur in shears in altered sediments and volcanic rocks.

A similar habit is evident in most of the deposits of the western trough of the Mount Isa Province, where the host structures are mostly strike slip faults in metasediments intercalated with more competent volcanic rocks. Brooks (1975) believes that the less competent sediments were disrupted preferentially during deformation.

The Mary Kathleen orebody is localized in a structural node in the Corella Formation. There is some dispute as to the precise geometry of the structure, but it is generally accepted to be a syncline (figure 4*d*). The garnetite that hosts the orebody passes laterally into a boulder conglomerate.

At Radium Hill (figure 3*b*) the orebodies are found along shears of regional dimensions (Sprigg 1954), and at Crocker Well the uranium mineralization occurs in fracture zones, breccias, and in dykes of aplite and pegmatite (King 1954). At Mount Painter and Olympic Dam the ore is emplaced in breccias.

Minor amounts of uranium mineralization occur, mainly in association with base metals, in shears in the metasediments of the Gawler Block and the Pine Creek Geosyncline, and in association with both pegmatites and planes of dislocation in other Proterozoic orogenic provinces.

From the above it may be seen that, almost without exception, the uranium mineralization occupies structural features that could have acted as channels to mineralizing fluids.

In the Alligator Rivers province the tops of the orebodies occur at or close to the unconformity at the base of the Carpentarian, although there is little evidence of the development of a regolith. At Jabiluka the ore zone extends to a depth of 600 m below the unconformity and at Ranger One No. 3 Orebody, ore is known 450 m below the present surface. In both cases the orebodies show every sign of continuation in depth with no diminution in grade. At Rum Jungle the Carpentarian is absent, the next youngest formation being the Depot Creek Sandstone which is currently thought to be of Adelaidean Age. The Eva Mine lies just below the Carpentarian unconformity, and the other deposits at Westmoreland occur just above it.

There is no evidence as to a relation between a younger unconformity and deposits at Mary Kathleen, Radium Hill, and Crocker Well. At Mount Painter the host rocks immediately overlie the unconformity between Adelaidean strata and the Nullaginian metamorphic basement.

Mineralization

The Australian continent has experienced prolonged exposure and erosion, and it is not inconceivable that in some parts of the Precambrian Shield there has been no inundation or substantial sedimentation since the Precambrian. It is not surprising, therefore, that there has been extensive superficial redistribution of uranium, particularly where the primary mineralization is uraninite or pitchblende.

Where the secondary ores comprise ochres, phosphates, carbonates, and other complex secondaries, a supergene origin is not in dispute and warrants no further discussion.

There are, in addition, some orebodies that are composed of pitchblende but in which the evidence for a supergene origin is strong. The best example is probably Rum Jungle Creek South, and it is notable that this deposit is free of those accessories found in most deposits, such as gold, a variety of sulphides, titanium oxides, apatite, and tourmaline. The orebody extends downwards from immediately below the base of weathering (figure 3*d*).

In a number of deposits it is clear that there has been supergene modification of earlier mineralization to a greater or lesser extent, and in such cases it may not always be easy to distinguish one generation of pitchblende from another. Furthermore both petrographic and geochronological evidence indicates either distinct phases of primary mineralization or episodes of rejuvenation. The presence of secondary sulphides such as covellite and chalcocite, of ochreous iron oxides, and of sooty, amorphous, and colloform pitchblende, raises doubts immediately as to the nature of the mineralizing process, but almost always the formation of these minerals is demonstrably superimposed on an earlier generation, or generations, of uranium, titanium, gold or sulphide mineralization, or combinations of all four. It is with this earlier mineralization that this paper is concerned.

A distinction is evident between what may be termed 'simple' ores in which pitchblende or uraninite is the primary uranium mineral and in which titanium, thorium and rare earths are absent or rare; and 'complex' ores in which uraniferous titanates predominate, or where rare earths are present. Gold, and cobalt and nickel sulphides, are mainly restricted to the simple ores. Apatite is almost universal, and even where it is not recorded, secondary uraniferous phosphates are common. Fluorite and barite are present at Olympic Dam and Mount Painter, and fluorapatite at Crocker Well. Tourmaline is recorded from Whites, Palette, Ranger One, Mary Kathleen, and Radium Hill, and thus transcends the division noted above. Clausthalite is present throughout the South Alligator Valley. Topaz has been recorded from the Eva Mine.

The simple orebodies are confined to the Pine Creek Geosyncline. At White's orebody the ore is zoned upwards from copper–uranium through a copper–cobalt zone and a cobalt–nickel zone, to an upper cobalt–lead zone. The zones are approximately parallel to the bedding (Spratt 1965). Roberts (1960) states that there was a primary phase of uranium mineralization, followed by sulphide mineralization, with a later minor phase of uranium emplacement or remobilization. Uranium minerals tend to occur in north-trending faults, and base metals in east-trending faults.

In the South Alligator Valley, pyrite, and cobalt and nickel arsenides, appear to be the earliest minerals, followed by a main pitchblende phase. Then followed the emplacement of chalcopyrite, galena-clausthalite, gold, and nickel-selenides, with a minor late pitchblende phase. At Palette the host rocks have been replaced by sericite, apatite and tourmaline (Threadgold 1960).

In the Alligator Rivers district, pitchblende predominates, with gold, and very minor amounts of galena (almost entirely radiogenic), chalcopyrite, and pyrite. Fander (1971) has noted epigenetic apatite and tourmaline, brannerite, and an amorphous uranium–titanium–phosphorus mixture at Ranger One. The minerals are unstressed and post-date the deformation of the host rocks. Dolomite veins are present at Ranger One, and at Jabiluka, where they intrude the Kombolgie Formation (Rowntree & Mosher 1975). Thucholite is present at Ranger One and at Hades Flat, between Ranger One and Jabiluka, in veins associated with pitchblende. Haematite occurs with pitchblende at all these deposits, and chloritization of the country rocks is widespread and profound.

Pitchblende, brannerite and uraniferous anatase are found at Westmoreland, together with altered titanomagnetite, haematite, galena, gold, chalcopyrite, gersdorffite, safflorite, pyrite and marcasite (Hills & Thakur 1975).

At Mary Kathleen, uraninite occurs as blebs in orthite (allanite) and in apatite, in a skarn composed of garnet, felspar, and scapolite. Stillwellite is present in isolated masses (Whittle 1960). Tourmaline, pyrite and chalcopyrite accompany the scapolite.

In the Eastern Creek Volcanics, brannerite is the most common mineral, associated with pyrite, galena, quartz, calcite, and various iron oxides and titanates. Many of the lodes are accompanied by carbonatization of the host rocks, and by quartz or siliceous jasper (Brooks 1975).

At Radium Hill, haematite, rutile and ilmenite, together with biotite and quartz, comprise an early generation of mineralization that is succeeded by a second phase which saw the formation of davidite, tourmaline, apatite, orthite, xenotime, pink felspar and 'newer' quartz (Whittle 1954*a*). Red felspar, late quartz, calcite, scapolite, and zeolite followed, together with minor sulphide minerals.

The ore mineral at Crocker Well is absite, a uranium–thorium titanate, and it resembles brannerite (King 1954). It is found with rutile, bronze biotite, blue opalescent quartz, and rarer apatite and davidite. Monazite, xenotime and zircon are also present.

Magnetite, with coeval or replacive haematite, appears to be the earliest mineral at Mount Painter, followed by monazite, and then the ore mineralizing phase which introduced chlorite, uraninite, and sulphides. Accessories include fluorite, ilmenite, allanite, barite, apatite, xenotime, and phlogopite. Secondary redistribution of uranium appears to have been more profound here than at most deposits, with an alteration of iron oxides and chlorite to iron ochres and vermiculite (Whitehead 1976).

Although little is known about the Olympic Dam orebody, in many respects the brief description available (S.A.D.M. 1977) indicates an affinity with the Mount Painter ores, though copper is much more common. Uraninite, with brannerite and davidite, occurs with pyrite, chalcopyrite, bornite, chalcocite, and digenite. Accessories include fluorite, barite, haematite with minor gold, carrolite, and cobaltite. Quartz and sericite compose the gangue.

Uraniferous Proterozoic pegmatites are known from the Mount Isa region, central Australia, and South Australia. The ore minerals are usually davidite or allanite. To date, nothing approaching economic significance has emerged.

Age

Pitchblende and galena ages in the Pine Creek Geosyncline have recently been reviewed by Hills & Richards (1976) together with the geochronology of the host rocks. The Nullaginian sediments were laid down in the period 2400–1800 Ma, at which latter time there was a fundamental metamorphic event, now represented by the Nanambu and Nimbuwah Complexes. Granite intrusion took place between 1830 and 1750 Ma. The mineralization at Ranger One dates at about 1700 Ma, with a suggestion of a sharp remobilization at about 900 Ma, with loss of lead. Galenas at Koongarra and pitchblende at the Tadpole prospect, north of Nabarlek, hint at a rather older age at 1850–1800 Ma. Interestingly the Tadpole (1850 Ma) correlates very well with the resetting of its host, the Nimbuwah Complex (1840 Ma).

At Koongarra a second event is recorded somewhere about 900–860 Ma.

Jabiluka, Nabarlek, and the South Alligator Valley deposits fall in the 920–800 Ma range. Steady lead loss is inferred for all these deposits subsequent to their deposition. The deposits at Westmoreland yield a similar age. A second event, at 500–400 Ma, is suggested in the South Alligator and at Westmoreland.

The Nullaginian Cliffdale Volcanics at Westmoreland and Tewinga Group at Mt Isa are coeval at about 1750 Ma and there are a number of granites that yield ages in the same period (Plumb & Derrick 1975).

The Burstall Granite, which intrudes the Mary Kathleen Group, dates at about 1400 Ma.

Cooper (1973) has reviewed and reassessed age determinations from the Willyama Complex. Ages from Crocker Well and Radium Hill indicate an original mineralizing event at 1700 Ma, with an episode of lead loss at about 500 Ma. The setting of the metamorphics of the Willyama Complex is indicated at about 1700 Ma.

Genesis

As mentioned earlier, many, if not all, of the pitchblende and uraninite deposits exhibit evidence of supergene processes, in the presence of sooty and colloform pitchblende (including replacement of uraninite by pitchblende), drusy and cavity fillings, sulphides such as covellite and chalcocite, ochreous iron oxides, and opalescent quartz. Some orebodies, such as Rum Jungle Creek South (R.J.C.S.) and Saddle Ridge, may have been entirely formed in this way, and it is certainly significant that they are devoid of base metal sulphides (R.J.C.S.) and gold (Saddle Ridge), as well as the refractory minerals, that are found in nearby deposits.

In the Pine Creek Geosyncline there are five major post-Nullaginian unconformities; at the base of the Kombolgie Formation (Carpentarian); at the base of the Tolmer Group (Adelaidean); at the base of the Daly River Group (Cambrian); at the base of the Cretaceous; and Tertiary to Recent. Significantly the three principal ages obtained from the deposits could be correlated with the first three unconformities noted above. The supergene pitchblende ores may relate to any or all of these periods.

Any explanation of the origin of what might be termed the primary 'simple' ores must take into account the following facts:

(1) the presence of base metal sulphides, selenides, arsenides, gold, titanates, phosphate and tourmaline, many of which post-date the uranium minerals;

(2) the presence of thucholite with gold and uranium (G. Taylor, personal communication);

(3) the alteration of the host rocks (variously: formation of chlorite, sericite, apatite, tourmaline, haematite, andalusite, kaolin, topaz, and clay materials);

(4) the apparent removal of carbonate, and replacement by silica;

(5) the chloritization, silification, and emplacement of dolomite, uranium, and gold in the base of the Kombolgie Formation;

(6) the presence of pitchblende veins, accompanied by chloritization and haematitization, in granite gneiss in the Nanambu Complex below the orebodies and elsewhere;

(7) the intrusive chlorite veins;

(8) the general association with unconformities, but also the depth of ore below them at Jabiluka and Ranger One;

(9) the fracturing of pitchblende at Rum Jungle and the South Alligator River;

(10) the chloritization of uraninite at Ranger One (Fander 1971);

(11) syneresis cracks in uraninite and pitchblende (Roberts 1960; Fander 1971);

(12) the apparent absence of a correlation between uranium and carbonaceous metasediments (Eupene *et al.* 1975), or between U, C and pyrite (Berkman 1968);

(13) the correlation between U and Pb, Th, V, Zr, Nb, and W in the Alligator Rivers province (J. Fergusson, personal communication);

(14) the stratiform habit of the lodes at Whites Mine;

(15) the absence of an obvious regolith in most places at the base of the Kombolgie Formation.

That these ores were introduced is not in dispute. It is the origin and nature of the mineralization that is the subject of considerable debate, and five principal possibilities have been mooted at various times.

(1) Magmatic, and genetically related to the Carpentarian Volcanics and/or the post-

tectonic biotite granites. Recent age determinations have ruled out this possibility for most of the deposits.

(2) Mineralization *per descensum* by leaching from the overlying Carpentarian sediments and intercalated volcanic members. Such an event has left absolutely no record of its passing and this theory cannot explain either the alteration at the base of the Kombolgie, including chlorite and dolomite veining, nor the emplacement of gold, sulphides, arsenides, etc. Moreover, there is no evidence of there having been volcanic rocks above the Rum Jungle deposits.

(3) Bulk remobilization of syngenetic ore, during deformation, from nearby sediments into suitable structural traps. A number of factors militate against this hypothesis. In some cases the mineralization predates the deformation, e.g. at Rum Jungle. In others, age dating indicates mineralization of a substantially younger age than the deformation. No protore of higher than average concentrations of uranium or base metal are known from what are postulated as the parent rocks elsewhere in the province. In fact, studies suggest that metal concentrations in metapelites are about average for rocks of this type. The correlation between U and such granophile elements as Zr, W, Nb, Th, and W could be said to argue against the hypothesis. Nevertheless it is likely that some tectonic remobilization has occurred, particularly at Rum Jungle. Here the stratiform nature of the ore; the copper–cobalt–nickel–lead–zinc lodes; the association with a negative structural feature; and the juxtaposition to a major fault; all could be said to point towards the syngenetic accumulation of metals on the sea floor.

(4) Leaching of metals from granitic terrain during period of exposure, and redeposition by meteoric water along the base of the Carpentarian or Adelaidean unconformity. Such a hypothesis fails to explain, in particular, the formation of refractory minerals (which are not susceptible to leaching today at least); the depth of apparently unoxidized ore; the introduction of base metal sulphides, selenides, and arsenides, in many cases after the deposition of pitchblende or uraninite; the extensive alteration of wall rock, including tourmalinization and apatitization; and the emplacement of chlorite and dolomite veins in the base of the Kombolgie Formation.

(5) The hydrothermal emplacement of the mineralizing fluids from sources unknown but most likely connected with granitization, anatexis, and expulsion of metal-bearing connate waters.

This last theory is consistent with all of the observed evidence. The objection most commonly raised is the spatial association with the unconformity, and the temporal association between periods of denudation and uranium formation. The extremely porous Kombolgie Formation could not have acted as an effective cap rock; on the contrary it must have been an effective aquifer. It is postulated that meteoric water accumulating in the Kombolgie Formation, and similar aquifers, mingled with rising hydrothermal fluids thus altering the physico-chemical conditions and causing precipitation of the metals. In this respect it is worth noting that Taylor (1968) has commented on the spatial relation between the Coronation Sandstone Member and underlying uranium deposits in the South Alligator Valley. Differential desorption of various metals from the sediment pile, as a function of progressively increasing dehydration and changing salinity in the slowly escaping connate water, could readily account for the different generations of mineralization at the deposition site (T. Healy, personal communication).

The source of these fluids is thought to be the granitized sediments. It may be no coincidence that the very large uranium bodies of the Alligator Rivers district overlie thick sequences of migmatite and granitized sediment. They also underlie thick Proterozoic sandstone formations.

Metamorphism in the Alligator Rivers region has reached the amphibolite facies, and only locally attains granulite facies. Migmatites and post-tectonic, probably anatectic, granites occur here as elsewhere in the Lower Proterozoic of Australia, and yet in other areas deposits are small, and the mineralization is more commonly of the refractory type.

At Radium Hill and Crocker Well there appears to have been a depletion of ferromagnesian minerals in the host paragneisses, and an enrichment of these elements in shears that transect them (Whittle 1954*a*). Uranium and titanium mineralization accompanies this mobilization. At Crocker Well the uranium is found in a comparable position and also in association with acid dykes that are themselves products of the granitization of sediments (Whittle 1954*b*).

Derrick (1977) and Whittle (1960) have thoroughly documented the metasomatism at Mary Kathleen. There can be little doubt that the formation of skarns and the emplacement of the ore minerals was associated with the intrusion of the nearby Burstall Granite and the porphyry dykes that extend from it.

Elsewhere in the Lower Proterozoic there are showings of uranium in shears in metamorphosed metasediments, usually in association with base metals. Stewart & Warren (1977) note the presence of uraniferous minerals in anatectic pegmatites in Central Australia. In the coeval Westmoreland Conglomerate and Eastern Creek Volcanics, the emplacement of uranium from underlying metamorphosed Nullaginian metasediments seems likely.

Smith (1974) has drawn attention to the propensity of uranium of occurring in provinces, and of recycling throughout the geological history of those provinces. It is postulated here that uranium, originally concentrated at normal levels in Nullaginian sediments, was either expelled during anatexis and hydrothermally emplaced in suitable structural traps, or carried along during the bulk remobilization of the granitized sediments. Where conditions were such that rapid dehydration was not possible, large deposits formed and the mineralization reflects the presence of abundant water. Where water escape was rapid, deposits were small, wall rock alteration is relatively minor, and the minerals tend to be refractory. Higher temperatures may have played a part. The intrusion of some completely remobilized granites was accompanied by metasomatism and uranium mineralization. It is noteworthy that in these cases there is also evidence of more abundant water with soda and chlorine metasomatism, and the introduction of rare earths, such as at Mary Kathleen and Mount Painter.

The widespread association of uranium deposits in the Proterozoic with basic rocks has been frequently commented on. Since granitization involves the explusion of ferromagnesian elements this should come as no surprise.

Perhaps the most intriguing point of all, however, is the great apparent difference in age between the Ranger One and Jabiluka deposits which are geologically extraordinarily similar. Eupene *et al.* (1976) have suggested that uraniferous fluids may have been stored in carbonate aquifers, where they would not precipitate, until tectonic activity, or perhaps degradation of the land surface, released them to points of deposition.

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References (Ryan)

Anthony, P. J. 1975 In Knight (ed.) 1975, pp. 304–308.

Berkman, D. A. 1968 In *Uranium in Australia* (eds D. A. Berkman, R. H. Cuthberg & J. A. Harris), pp 12–31. Melbourne: Aust. Inst. Min. Metall.

Brooks, J. H. 1975 In Knight (ed.) 1975, pp. 396–397.

Carter, E. K. Brooks, J. H. & Walker, K. R. 1961 *Aust. Bur. Min. Resour. geol. geophys. Bull.* 51.

Cooper, J. A. 1973 In *Stratigraphic problems of the late Precambrian and early Cambrian*, Univ. Adelaide Centre for Precambrian Research, Spec. Pap. no. 1, pp. 63–69.

Derrick, G. M. 1977 *B.M.R. J. Aust. Geol. Geophys.* **2**, 123–130.

Dow, D. B. & Gemuts, I. 1969 *Aust. Bur. Min. Resour. geol. geophys. Bull.* 106.

Eupene, G. S., Fee, P. H. & Colville, R. G. 1975 In Knight (ed.) 1975, pp. 308–317.

Eupene, G. S., Fraser, W. J. & Ryan, G. R. 1976 Alligator River type uranium deposits (unpublished). Hobart Aust. N.Z. Ass. Adv. Sci.

Fander, H. W. 1971 Report to Geopeko Limited, Central Miner. Services Pty Ltd Rpt. 71/5/41 (unpublished).

Fisher, N. H. & Warren, R. G. 1975 In Knight (ed.) 1975, pp. 27–40.

Foy, M. F. & Pederson, C. P. 1975 In Knight (ed.) 1975, pp. 317–321.

Fraser, W. J. 1975 In Knight (ed.) 1975, pp. 271–277.

Hills, J. H. & Richards, J. R. 1976 *Miner. Deposita* **11**, 133–154.

Hills, J. H. & Thakur, V. K. 1975 In Knight (ed.) 1975, pp. 343–347.

Johns, R. K. 1961 *S. Aust. geol. Surv. Bull.* 37.

King. D. 1954 *S. Aust. geol. Surv. Bull.* 30, pp. 70–78.

Knight, C. L. (ed.) 1975 *Economic geology of Australia and Papua New Guinea*. Melbourne: Australian Institute of Mining and Metallurgy.

Orridge, G. R. & Mason, A. A. C. 1975 In Knight (ed.) 1975, pp. 339–343.

Plumb, K. A. & Derrick, G. M. 1975 In Knight (ed.) 1975, pp. 217–252.

Roberts, W. M. B. 1960 *Neues Jb. Miner. Abh.* **94**, 868–889.

Rowntree, J. C. & Mosher, D. V. 1975 In Knight (ed.) 1975, pp. 321–326.

Ryan, G. R. 1977 In *Geology, mining and extractive processing of uranium* (ed. M. J. Jones), pp 24–42. London: Instn Min. Metall.

S.A.D.M. 1977 South Australian Department of Mines circular (unpublished).

Smart, P. G., Wilkes, P. G., Needham, R. S. & Watchman, A. L. 1975 In Knight (ed.) 1975, pp. 285–301.

Smith, E. E. N. 1974 In *Formation of uranium ore deposits* (IAEA-SM-183/45), pp. 515–529. Vienna: Int. Atomic Energy Agency.

Spratt, R. N. 1965 In *Geology of Australian ore deposits* (ed. J. McAndrew) (8th Commonwealth Min. Metall. Congr., Melbourne), pp. 201–206.

Sprigg, R. C. 1954 *S. Aust. geol. Surv. Bull.* **30**, 7–50.

Stanton, R. L. 1976 *Trans. Instn Min. Metall.* **85**, B221–B223.

Stewart, A. J. & Warren, R. G. 1977 *B.M.R. Jl Aust. Geol. Geophys.* **2**, 21–34.

Taylor, J. 1968 In *Uranium in Australia* (eds D. A. Berkman, R. H. Cuthbert & J. A. Harris), pp. 32–44. Melbourne: Aust. Inst. Min. Metall.

Thomson, B. P., 1973 Ore deposits in relation to the tectonic development of eastern Australia. *Aust. Bur. Min. Resour. geol. geophys. Bull.* **141**, 95–105.

Thomson, B. P. 1975*a* In Knight (ed.) 1975, pp. 461–466.

Thomson, B. P. 1975*b* In Knight (ed.) 1975, pp. 451–454.

Thomson, B. P. 1975*c* In Knight (ed.) 1975, pp. 469–476.

Threadbold, I. M. 1960 *Tech. Pap. Mineragraphic Invest. C.S.I.R.O.* no. 2.

Walpole, B. P., Crohn, P. W., Dunn, P. R. & Randall, M. A. 1968 *Aust. Bur. Min. Resour. geol. geophys. Bull* **82**.

Whitehead, S. 1976 Aust. Miner. Devel. Labs Rept MP2714/76 (unpublished).

Whittle, A. W. G. 1954*a* *S. Aust. geol. Surv. Bull.* **30**, 51–69.

Whittle, A. W. G. 1954*b* *S. Aust. geol. Surv. Bull.* **30**, 79–83.

Whittle, A. W.G. 1960 *Neues Jb. Miner. Abh.* **94**, 798–830.