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'Unconformity-related' U ± Au ± platinum-group-element deposits

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EXPLORATION MODEL

Examples

Jabiluka, Ranger, Coronation Hill, Koongarra, Nabarlek, Rum Jungle (Australia); Rabbit Lake, P2 North, Eagle Point, Dominique-Peter, Claude, Cluff (Canada)

Target

- Typical size: 0.1–20 Mt of ore.
- Both single and multiple deposits occur.
- Grade: 0.2–12% U.
- May have up to 200 ppm Au and 30 ppm PGE.

Mining and treatment

- U usually in stratiform wedge or tabular form, but Au and PGE may be more widespread (Fig. 1).
- U is readily separated and recovered by acid leaching of ore, followed by solvent extraction.

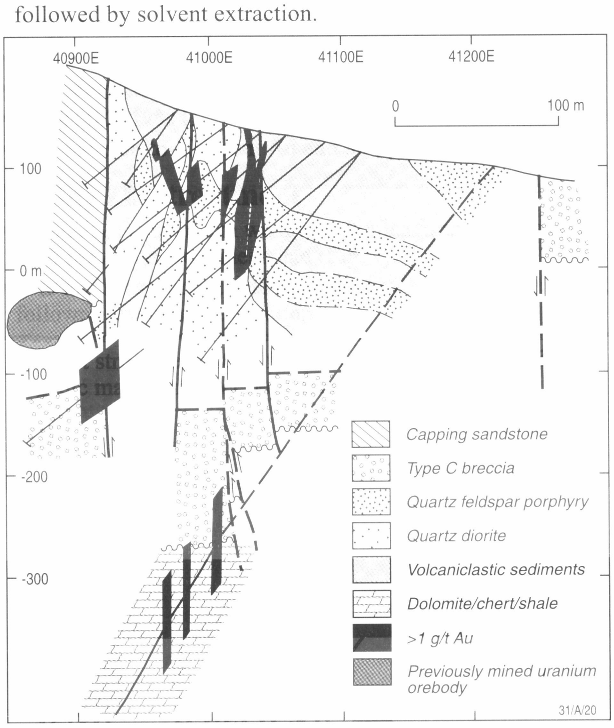

Figure 1. Composite cross-section (looking N) of the Coronation Hill prospect.

Regional geological criteria

- Intracontinental or continental margin basins.
- An oxidised, thick cover sequence (>1 km) of quartz-rich sandstone.
- Reduced basement, containing feldspar-bearing rocks or carbonaceous/ferrous iron-rich units.
- Dilatant structures within faults which cut both cover and basement sequences.

Local geological criteria

- An unconformity or fault separating reduced lithologies from an oxidised cover sequence.
- The largest Australian deposits lie within 100 m of an unconformity.
- Sub-vertical and sub-horizontal pipe-like or ribbon-like dilatant structures within faults or sandstones containing organic matter or other reductants.

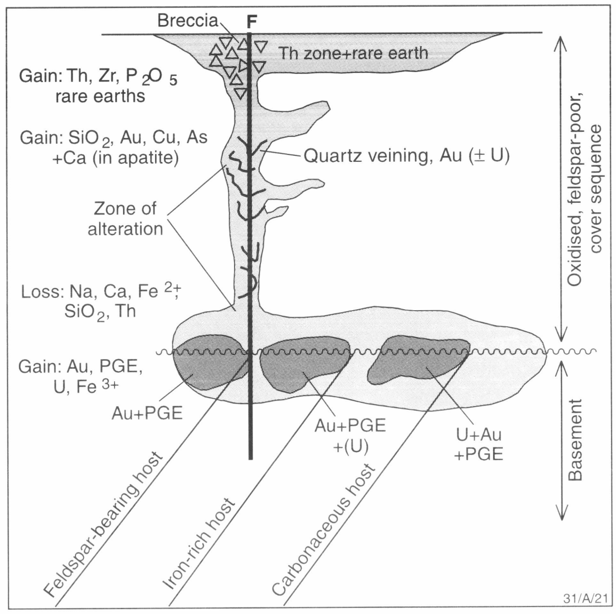

Figure 2. Model of possible relationships between different styles of unconformity-related U ± Au ± PGE deposits.

- Mineralisation of major deposits is older than 500 Ma, with the majority 1350–1750 Ma.

Mineralisation features

- Hosted by veins, and open space-filling breccia
- Primary minerals are uraninite, Au, Pd, stibiopalladinite, and Pt–Pd selenides.
- Gangue minerals include chlorite, sericite, quartz, carbonate, graphite, kaolinite, hematite.
- Au ± PGE only ore is hosted by feldspathic and calcareous rocks.
- U ± Au ± PGE ore occurs in reduced lithologies, typically at or below a regional unconformity.
- Low sulphide content with minor pyrite, galena, marcasite, pyrrhotite, sphalerite, and chalcopyrite.

Alteration

- Alteration extends over 1 km from the mineralisation.
- Alteration characterised by sericite–chlorite ± kaolinite ± hematite.
- Mg metasomatism and the formation of late-stage Mg-rich chlorite is common.
- Strong desilicification occurs at the unconformity, and quartz is redeposited as veins at higher stratigraphic levels.

Deposit geochemical criteria

- U and Mg enrichment in alteration zones adjacent to mineralisation with accompanying SiO_2, Na_2O, CaO, and Th depletion.
- Anomalous Th concentrations above deposits.
- Cu, Au, and As precipitate at higher stratigraphic levels and phosphatic breccias occur at even higher levels.
- Enhancement of Ni and Cr in mafic rocks, Ba and P_2O_5 in feldspar-rich rocks, and Mn in iron-rich rocks.

Surficial geochemical criteria

- Stream sediments may show anomalous U and/or Au, but other trace elements are influenced by the dominant lithology in the drainage basin.
- Soil sampling indicates that U anomalies associated with mineralisation can be distinguished from areas of high natural U by high U/Th.
- Rock-chip surveys show enrichment in As, Cu, La, Ce, Nd, Sr, Zr, Cr, Ni, Ba, Mn and P_2O_5 associated with mineralisation.

Geophysical criteria

- U, U^2/Th, and U^2/K are the most useful gamma-ray spectrometry images for highlighting alteration and mineralisation.
- Areas of high Th, but low U and K may also indicate mineralisation at depth.
- Magnetic lows resulting from the formation of hematite from oxidised fluids are visible in aeromagnetic data.
- Some deposits occur in the vicinity of conductive (graphitic) horizons, which give a distinct response in ground electromagnetic surveys.

Fluid chemistry and source

- Highly saline, Ca-dominated fluids, up to 30 wt % $CaCl_2$.
- Moderate temperature, 100–200°C.
- Oxidised and acidic (pH<5).
- Meteoric fluid with $\delta^{18}O$ values between –6 and +1 per mil.
- Au ± PGE-only ore is precipitated by moderate decrease in pH/fO_2 by interaction with feldspathic or pH-neutralising lithologies.
- U ± Au ± PGE precipitates when an oxidised fluid mixes with reduced fluids or directly interacts with reduced lithologies.

Comments on genesis

- The '***meteoric model***' (Johnston & Wall 1984, Wilde et al. 1989a, Jaireth 1992, Solomon & Groves 1994, Mernagh et al. 1994, Komninou & Sverjensky 1996). Highly oxidised, acidic and Ca-rich meteoric brine in a neutral cover sequence flows down faults and dilational structures. Fluid interaction with feldspathic or calcareous rocks causes a moderate increase in pH and reduction in fO_2 leading to precipitation of Au and PGE, but little or no U. Mixing with reduced fluids from below the unconformity or direct interaction with carbonaceous or other reduced basement lithologies causes precipitation of U + Au + PGE. This model explains the observed wider distribution of Au + PGE ore and the restriction of U + Au + PGE ore to at or below the unconformity.
- The '***diagenetic model***' (Hoeve et al. 1980, Sibbald & Quirt 1987, Ruzicka 1993). Oxidised, ore-bearing fluids form within the sedimentary cover during high-temperature prograde diagenesis. Some of the fluids enter the basement and are reduced before ascending again along faults and fractures, where they mingle with laterally moving oxidised fluids. Precipitation of U + other metals takes place at the interface between the oxidising and reducing fluids (i.e. at the redox front). High-grade U or polymetallic mineralisation forms directly at the unconformity. Medium-grade U mineralisation may form below the unconformity and low-grade U mineralisation may form within the sedimentary sequence at some distance above the unconformity. However, this model does not account for the Au + PGE mineralisation (without U) which occurs above the unconformity at Coronation Hill.
- The '***supergene model***' (Ferguson et al. 1980, Knipping 1974, Ruzicka 1975). U + other metals are leached from Palaeoproterozoic rocks by surface waters and precipitated when they encounter a reducing environment. The timing is presumed to be pre-deposition of overlying sediments, i.e., during formation of the regolith at the unconformity, but recent dating indicates that mineralisation post-dates the age of the overlying sediments for most of the 'unconformity-related' deposits.
- The '***hypogene model***' (Hegge & Rowntree 1978, Binns et al. 1980). Heat generated from adjacent granites drives a convective cell of metalliferous fluids. The source of the fluids is considered deep-seated, generated during the metamorphic event preceeding deposition of the overlying sediments. This model cannot satisfactorily account for the spatial association of mineralisation with the unconformity between basement and overlying sediments.

Introduction

'Unconformity-related' deposits constitute approximately 33% of the World Outside the Centrally Planned Economies Area's (WOCA's) U resources and they include some of the largest and richest deposits (Lambert et al. 1996). Although U is usually the principal commodity, many Australian deposits also contain significant quantities of Au and platinum group elements (PGE), which are paragenetically associated with U mineralisation, but not necessarily spatially associated with the U. For example, the Jabiluka deposit contains ~93 000 t U_3O_8 and 8.8 t Au, and significant but subeconomic Pd (Wilkinson 1995, Wilde et al. 1989a). Many of the Canadian deposits also contain significant quantities of Au, PGE and other metals, such as Ni, Co, Cu, Zn, etc. (Ruzicka 1993). In the Pine Creek Inlier, the mineralisation is typically concentrated at the base of a Paleoproterozoic sandstone, where it is in unconformable contact with older basement rocks, which commonly contain carbonaceous and/or ferrous iron-rich rocks. In the early 1970s, deposits of this type became very attractive exploration targets, but suitable geological environments for these types of deposit seem relatively restricted. Within the Pine Creek Inlier (see below) there are over 100 U-bearing occurrences, over 70 of these being in the Alligator Rivers uranium field (Ewers et al. 1984). This review attempts to summarise some of the features common to Australian Proterozoic, 'unconformity-type' deposits and also includes some younger U deposits that have similar mineralisation processes.

Australian regional setting

Deposits in the Pine Creek Inlier

The major U occurrences in Australia are shown in Figure 3, and those in the Pine Creek Inlier in the Northern Territory can be divided into three fields (Fig. 4): the Rum Jungle uranium field, the Alligator Rivers uranium field and the South Alligator Valley mineral field. Geologically, this region is dominated by Paleoproterozoic sedimentary and volcanic rocks, which were deposited on a basement of deformed Archaean metasediments and felsic meta-igneous rocks. The earliest sedimentation took place in intracratonic basins. The basal sequence overlying the Archaean Waterhouse and Rum Jungle Complexes, the Namoona Group, contains sandstone, arkosic conglomerate, minor shale and massive marble (Needham et al. 1980). In the northeast, the Kakadu Group, which is composed of mainly gneiss and quartzite, is the basal sequence which surrounds the Nanambu Complex. The lower member of the Cahill Formation overlies the Kakadu Group and is the main host for U mineralisation in this region (Needham et al. 1980). It contains carbonaceous schist, marble, calc-silicate rock, paragneiss and carbonate lenses, which commonly occur near the ore zones. These groups are further overlain by fluviatile and shallow marine sequences of psammites and pelites (Needham et al., 1980).

This first period of Paleoproterozoic sedimentation was followed by regional metamorphism and a major phase of deformation, the Nimbuwah event, at about 1865 Ma (Needham et al. 1988). In the South Alligator Valley region, the pre-1865 Ma sequence is unconformably overlain by the El Sherana and Edith River Groups, which are dominated by felsic volcanic rocks. Widespread granite intrusions are associated with broad refolding, which occurred around 1830 Ma (Stuart-Smith et al. 1993). Above the volcanics and the pre-1865 Ma sequence is a second regional unconformity and the Katherine River Group, which consists of flat-lying, hematitic sandstone of the Kombolgie Formation and some interbedded mafic volcanic rocks. Note that the Katherine River Group does not extend into the Rum Jungle area.

The ***Rum Jungle uranium field***, in the western part of the Pine Creek Inlier, was the site of the earliest discovery of U in the Pine Creek area in 1949. Subsequently, several small deposits (the largest of which contained ~2400 t U) were mined in this region, e.g. Rum Jungle Creek South, Whites, Dysons and Mount Burton.

The ***Alligator Rivers uranium field*** lies in the northeastern part of the Pine Creek Inlier and contains the largest known U deposits (e.g. ~93 000 t U_3O_8 at Jabiluka) in the inlier. The major mineral deposits in this field (e.g. Koongarra, Ranger, Jabiluka, and Nabarlek) are located in or adjacent to fault zones. These deposits have an outer zone of alteration extending over 1 km from the ore, which is also associated with a more restricted inner zone of alteration in the basement, and along and above the unconformity below the Kombolgie Formation (Gustafson & Curtis 1983, Wilde & Wall 1987, Wilde et al. 1989a). Mineralisation occurs below the unconformity between the Cahill Formation and the Kombolgie Formation and is close to and often within graphitic horizons in the pre-1865 Ma sequence. The earliest phases of mineralisation at Koongarra, Jabiluka and Nabarlek have been shown by U–Pb and Sm–Nd age determinations to be about 1615 Ma (Maas 1989), but mineralisation at Ranger appears to be older than the ~1650 Ma Kombolgie Formation (~1737 Ma, Ludwig et al. 1987, Maas 1989).

The ***South Alligator Valley uranium field*** lies within the major northwest-trending Rockhole–El Sherana–Palette fault system. All deposits are small but high grade and the largest production of 192 t U was from ore grading 0.47% U from the El Sherana deposit (Battey et al. 1987). The host rocks are greenschist facies, but the deposits are also surrounded by alteration zones, which may extend for >1 km. The alteration is characterised mineralogically by quartz + sericite ± chlorite ± kaolinite ± hematite, with hematite being the most extensive type of alteration. U–Pb dating indicates that mineralisation is much younger than in the Alligator Rivers uranium field and may be as young as 600–900 Ma (Greenhalgh & Jeffery 1959).

Other similar Australian uranium deposits

The ***Turee Creek*** area is located in the Pilbara region of Western Australia, near the southern margin of the Hamersley Basin, adjacent to the Bresnahan Basin. The area contains an estimated 0.5 Mt U_3O_8 with an average grade of 0.45 kg/t (Wilkinson 1995). The most significant mineralisation is in the Angelo River area, at the faulted contact (unconformity?) between underlying dolomite and carbonaceous shales of the Paleoproterozoic Wyloo Group and the overlying Mesoproterozoic Kunderong Sandstone. Near-surface, oxidised, acidic groundwaters moving along the contact are thought to have transported U, which was deposited and further concentrated in response to pH increasing from interaction of the fluid with the wall rocks (Ewers & Nakatsuka 1986).

The ***Kintyre*** deposit is located in the Rudall region of the Paterson Province, north Western Australia. It was discovered in 1985 and has a resource estimate of 36 000 t U_3O_8 with grades of 1.5–4.0 kg/t U_3O_8 (Jackson & Andrew 1990). Basement rocks in this region consist of high-grade isoclinally folded metasediments (Rudall Metamorphic Complex), which are unconformably overlain by Neoproterozoic sedimentary rocks (Coolbro Sandstone, Yeneena Group). Unlike the cover sequence in the Pine Creek Inlier, the overlying Coolbro Sandstone has been tightly folded and sheared. The ore is hosted by graphitic schist, and chloritic and carbonaceous schist, chert, pelite and psammite in the basement Rudall Metamorphic Complex; hematite and carbonates occur immediately around mineralised veins. Mineralisation occurs as colloform uraninite in dolomitic carbonate veins, with lower grade disseminated uraninite. Accessory to trace native Bi, chalcopyrite, bornite, galena and Au are associated with uraninite, and platinoids have been detected.

The ***Westmoreland*** uranium field comprises a series of small prospects and deposits near the southeastern margin of the McArthur Basin, near the Queensland/Northern Territory border. The estimated reserves for the principal U deposits total 12 000 t of ore grading 0.17% U_3O_8. The U mineralisation is located near

Figure 3. Major 'unconformity-related' U deposits and prospects in Australia (modified from Battey et al. 1987).

the Westmoreland Conglomerate, in the underlying Cliffdale Volcanics (e.g. Eva mine), the overlying Seigal Volcanics (e.g. Cobar 2), or in the Westmoreland Conglomerate adjacent to the northeast-trending basic dykes. Hochman & Ypma (1984) concluded that U was leached from the Westmoreland Conglomerate and was precipitated where suitable reducing conditions existed. Ahmad (1987) advocated a similar origin and elaborated on the precipitation mechanism.

The ***Tennant Creek***-style of mineralisation has also been described as a variant of 'unconformity-related' U±Au±PGE mineralisation (Wall & Valenta 1990). At the Edna Beryl and Northern Star prospects, U is associated with Au in hematitic shale of the Warramunga Group, which is unconformably overlain by several cover successions, including the Tompkinson Creek beds. Wall & Valenta (1990) claim that the ironstone bodies formed in tension cracks and dilatant fault jogs. The deformation of the chloritic shear-zone envelopes around the ironstones allowed ingress of an acidic, oxidised, highly saline fluid which was capable of simultaneously transporting Au, Cu, Bi and U. Mineralisation is thought to be due to reduction of these fluids by reaction with the magnetite-rich ironstones (Wall & Valenta 1990). Khin Zaw et al. (1994) have shown that the ore-bearing fluids at Tennant Creek were oxidised, highly saline brines, and Huston et al., (1993) argued that mineralisation resulted from the ascent of oxidised high-temperature magmatic fluids which mixed with reduced connate brines. The latter authors claim that the type of ore formed depended on the ratio of the two fluids. Skirrow & Walshe (1994) have proposed another model, which has an oxidising, highly saline, basinal brine present prior to and during ore deposition, but with Au ± Bi ± Cu mineralisation resulting from an ascending, hotter, reduced fluid which was subsequently oxidised by the ironstone bodies. For all cases, however, chemical modelling has shown that relatively oxidised fluids (i.e. fO_2 > hematite–magnetite buffer) are required for U transport (Dubessy et al. 1987).

107 U occurrences (Battey et al. 1987) are recorded in the Eastern Creek Volcanics of the Mt Isa region. The largest of these is ***Valhalla*** with an indicated resource of 8.69 Mt of ore grading ~1% U_3O_8. The U ore occupies a steeply dipping ferruginous tuff horizon interbedded with metasediments and pyritic shale, and minor Cu mineralisation is present in the form of chalcopyrite–silica–dolomite veining (Wilkinson 1995). Nearby deposits include the ***Skal*** deposit, where U occurs in a brecciated siltstone interbedded with basic volcanics, and the ***Anderson's Lode*** prospect, which contains U mineralisation in a lens of altered greywacke interbedded with altered basalt (Battey et al. 1987). Recently, Heinrich et al. (1995) have shown that the district-scale alteration of metabasalts in the Eastern Creek Volcanics was associated with the infiltration of bittern brines. The high ferric/ferrous ratio of the altered basalts kept these brines at moderately high oxidation potentials, which were favourable for the transport of Cu, U and other elements that could be leached from the source rocks. The oxidised brine is

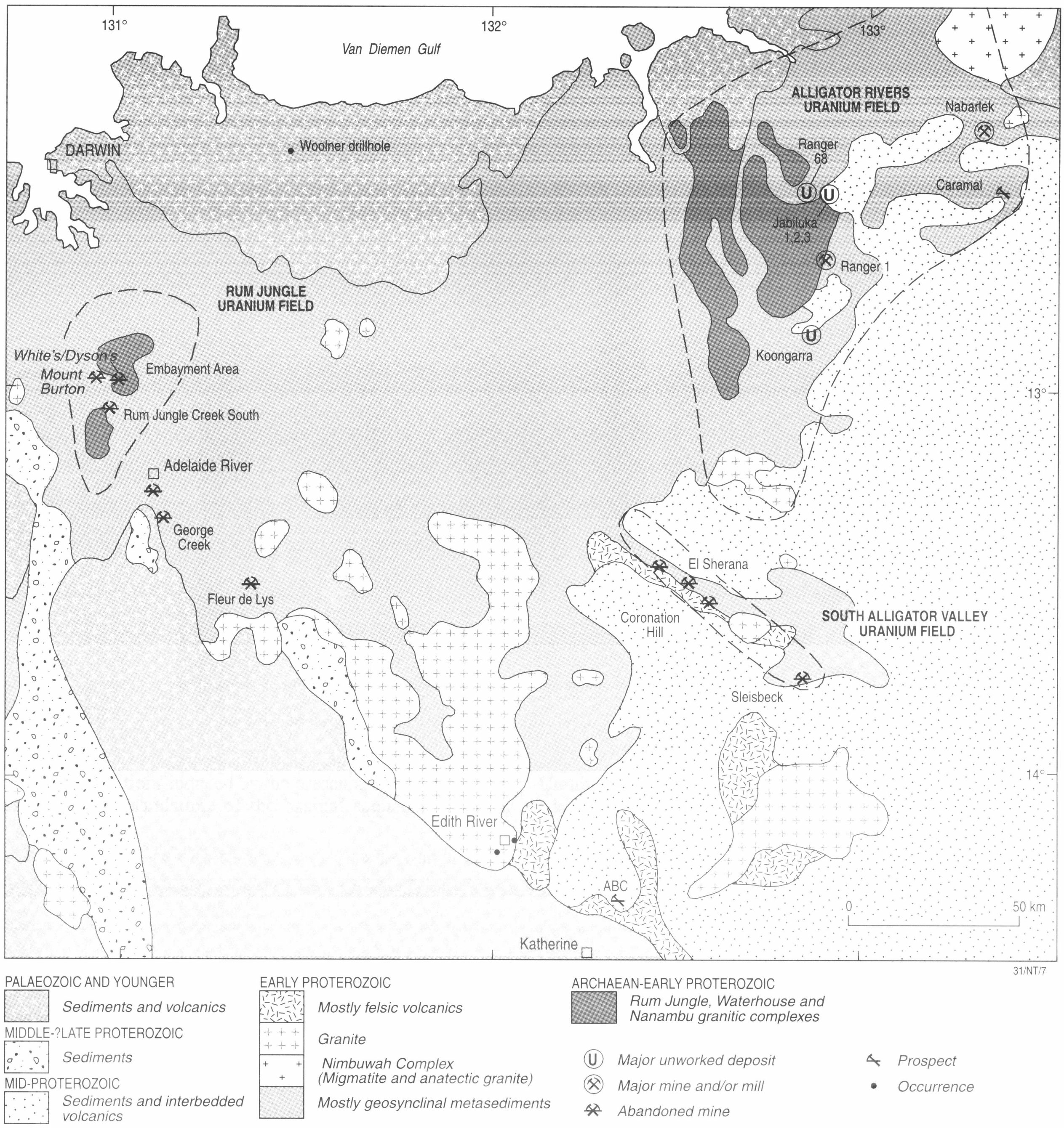

Figure 4. Simplified geology and location of the three main U fields in the Pine Creek Inlier (modified from Battey et al. 1987).

thought to have initially flowed downwards before being refocussed along major faults (Heinrich et al. 1995) and, thus, U mineralisation may occur at relatively low temperatures wherever these downdrawn fluids encounter suitably reduced (i.e. graphitic or ferrous-rich) sediments, volcanics or dolerites.

The ***Bigrlyi*** U deposit in the Ngalia Basin is an example of a much younger deposit, which contains ~2770 t U_3O_8 (Fidler et al. 1990). The ore is hosted by organic-rich sandstone in the Devonian–Carboniferous Mount Eclipse Sandstone. However, the mineralisation at Bigrlyi occurs in the middle of the sedimentary basin, approximately 100–500 m above the unconformable contact with the metamorphosed basement, rather than at or below the unconformity, as in the above examples. This difference is attributed by Fidler et al. (1990) to mineralised, oxygenated, meteoric waters descending into the basin and encountering reducing conditions induced by the presence of organic matter trapped in the sandstone of the basinal sequence. Another example of the Bigryli style of deposit is the ***Oobagooma*** prospect in the West Kimberley region (Brunt 1990). This is hosted by Late Devonian–Early Carboniferous sandstone, within a Phanerozoic basin. Groundwater has migrated along the palaeochannel and formed a broad tongue of oxidised sandstone. Uranium mineralisation precipitated in and around concentrations of detrital organic matter in this oxidised sandstone.

The Frome Embayment in South Australia contains even younger deposits. The ***Beverley*** deposit (~16 200 t U_3O_8) comprises several large flat-lying lenses of U mineralisation in a quartz–feldspar sand unit of the Namba Formation (Miocene). Organic carbon ranges up to 0.5% in the mineralised zones (Battey et al. 1987). The ***Honeymoon*** deposit (~3390 t U_3O_8) is in a paleochannel at the margins of a zone of oxidised sand and clay of the underlying Eyre Formation (Palaeocene–Eocene). Uranium was precipitated at a redox boundary along the outer edge of a broad bend in the channel. The oxidised sand is yellow and orange, owing to the presence of limonite, and the reduced sand is grey and pyritic. Carbon, mostly as organic plant matter, remains in the reduced zones (Battey et al., 1987).

Controls on mineralisation

Structural controls

All deposits appear to be structurally controlled and lie close to major faults that intersect both the basement and the overlying sedimentary cover sequence (Johnston & Wall 1984, Valenta 1991). Within these major fault structures U mineralisation was localised in kinked, chevron-folded and brecciated regions in the basement lithologies. In the South Alligator Valley, mineralisation was localised around two types of opening: 1) sub-horizontal pipe or ribbon-like bodies, which do not extend at depth, but are laterally extensive; and 2) sub-vertical pipe-like features, which have a small horizontal expression, but extend to greater depth than the former type (Valenta 1991). The faults controlling mineralisation were active after deposition of the cover sequence above the unconformity. They may be reactivated earlier faults or younger faults post-dating deposition of the cover sequence. Generally, there is little post-unconformity displacement on these faults (Valenta 1991), which acted as a conduit for the ore-bearing fluids.

Lithological controls

The role of the basement lithologies. All known U deposits of the Pine Creek Inlier lie below, but within 100 m of the unconformity between post-1865 Ma sandstones and felsic volcanics and the pre-1870 Ma highly deformed basement. Mineralisation in the Rum Jungle region is confined to pyritic, chloritic and graphitic phyllites. In the Alligator Rivers uranium field, mineralisation at Nabarlek is associated with chlorite and white mica in a shear zone in altered schists, while all other deposits occur in the lower member of the Cahill Formation, which consists of alternating quartz–muscovite–chlorite schist, quartz–chlorite schist, quartz–graphite schist, and magnesite dolomite. In the South Alligator Valley, U mineralisation is hosted in carbonaceous, iron-rich and chloritic shales. In contrast to this, Au and PGE mineralisation without U is hosted by feldspathic and calcareous rocks and, at Coronation Hill, the host lithologies for the Au + PGE-only mineralisation include quartz–feldspar porphyry, green tuffaceous shale, diorite, dolomite and sedimentary breccias.

In summary, deposition is related to redox/pH changes resulting from either fluid mixing or fluid interaction with host lithologies. These lithologies can be divided into those dominated by reductants (e.g. graphite, pyrite, etc.), which host mainly U deposits, and those capable of neutralising the acidic ore-bearing fluids (e.g. feldspars, carbonates, etc.). The latter tend to host Au and PGE dominant ore deposits. In higher flow regimes, deposition may be totally independent of the host rocks and, instead, occurs as a result of mixing between oxidised and reduced fluids.

The role of the cover sequence. A thick, neutral to oxidised cover sequence (such as the Kombolgie Formation) played an important role in the formation of world-class ‘unconformity-style’ deposits. Physically, it acted as a thick but permeable cover sequence, forming a substantial reservoir which allowed the prolonged maintenance and concentration of fluids in an oxidised, metal-rich state before migration into more reducing environments below (Mernagh et al.1994). The thick cover sequence also acted as an insulating blanket, such that the meteoric fluids could attain temperatures around 150°C as they flowed down faults towards the unconformity. These temperatures are optimal for the simultaneous transport of U, Au and PGE as the solubilities of U and PGE decrease at higher temperatures (Wilde et al 1989a). Thirdly, the thick sandstone cover sequence acted as a protective cap which preserved the ore deposits for a considerable period of time from the effects of later erosion.

The non-reactive nature of the quartz-rich sandstones of the Kombolgie Formation ensured that the highly oxidised environment necessary for optimum U transport was maintained. If the solutions were to come into contact with large volumes of carbonaceous material, ferrous iron, carbonate, feldspar or sulphides within the cover sequence, then precipitation of metals from the fluid in a disseminated form would occur throughout the cover sequence. The absence of clay in the Kombolgie Formation allows the sandstone to maintain its permeability, whilst the absence of feldspar maintains the low pH conditions needed to keep the metals in solution. As a result, there is no mineralisation within the Kombolgie Formation, although some alteration extends into it (Gustafson & Curtis 1983). This contrasts with the Canadian unconformity-style deposits, where ore occurs both in the basement and in the cover sequence in sandstones of the Athabasca Formation. This difference is due to the presence of reductants such as carbon, organic material and ferrous minerals in the Athabascan sandstones, which are also believed to have contained a high proportion of feldspar and mafics prior to diagenetic alteration (Hoeve et al. 1980).

What is the role of the unconformity?

The role of the unconformity is two-fold (Johnston & Wall 1984). Firstly, it represents a chemical contrast between neutral or non-reactive rocks above the unconformity, and chemically reactive basement rocks immediately below it. The ore-bearing fluid is largely unaffected as it passes through the non-reactive rocks above the unconformity and, hence, there is normally no mineralisation within the cover sequence. However, chemical reactions leading to the precipitation of ore may occur whenever the fluid interacts with the feldspathic or reducing lithologies. This normally happens when the ore-bearing fluid encounters different lithologies below the cover sequence; but there are exceptions to this rule (e.g. deposits in the Athabasca Formation, Bigrlyi, etc.) which occur when the reductants are incorporated within the cover sequence itself.

The second role is that of strain incompatibility, which occurs between the basement and the cover rocks at the unconformity. This incompatibility enhances permeability so that the unconformity acts as a pathway for mineralising fluids and it follows that unconformity-style deposits could also form well below the unconformity (e.g. adjacent to faults) in regions where there are strong competency and/or chemical contrasts.

Therefore, although most of the known U deposits are at or just below the unconformity, as such, it is not an essential feature, as mineralisation will occur whenever there are strong chemical contrasts between the ore-bearing fluids and their surrounding environment.

Hydrothermal alteration haloes

The orebodies are ringed by patchy alteration zones, which may extend over 1 km from the site of mineralisation (Binns et al. 1980, Gustafson & Curtis 1983, Wilde & Wall 1987). The alteration is characterised by sericite–chlorite ± kaolinite ± hematite (Binns et al. 1980, Wilde & Wall 1987, Wyborn et al. 1991). Strong desilicification occurs at the unconformity and silica is redeposited as quartz veins at higher stratigraphic levels (Wilde & Wall 1987, Wyborn et al. 1994). The alteration zones are also enriched in Mg and have high Fe^{3+}/Fe^{2+} ratios, owing to the oxidation of nearly all Fe present in this zone (Ewers & Ferguson 1980). They also have high U/Th ratios, and almost complete depletion of Na_2O, CaO and Th (Wilde et al. 1989a, Wyborn et al. 1994). Depletion of Th in the alteration zones implies that Th must have been precipitated elsewhere. Th-enriched areas have been located at higher structural levels and are generally associated with high concentrations of rare-earth elements and Zr (Fig. 2). Thus, zones of Th enrichment and silicification may be potential indicators of unconformity-related mineralisation at depth.

Phosphorus is also markedly enriched at some deposits (e.g.

Ranger, Jabiluka and Koongarra) and at Nabarlek it occurs mainly as apatite (Frishman et al. 1985). In the South Alligator Valley, many deposits have consistently high P values (up to 17 wt.% P_2O_5) and high concentrations of phosphate (up to 38 wt.% P_2O_5) are also known to occur in sandstone and breccia in the Rum Jungle area (Ingram 1973). This enrichment of P appears to occur at structurally higher levels than the mineralisation (Wyborn et al. 1991) and, thus, outcrops of P_2O_5, particularly those near faults, may indicate mineralisation at depth.

Ore mineralogy

Uraninite is the most common primary U mineral, but minor brannerite, coffinite, and other secondary U minerals formed by weathering may also occur. In the Rum Jungle uranium field, U is locally accompanied by base-metal sulphides in various proportions (Needham & De Ross 1990). Uranium mineralisation occurs as veins, breccia fill and fine-grained disseminations in the Alligator Rivers uranium field and the U is accompanied by Au at Koongarra and Ranger (Wilde 1991). Both Au and minor PGE mineralisation occur with U ore at Jabiluka and Nabarlek (Wilde et al. 1989a). At Koongarra and Nabarlek, fine Au grains are included in uraninite, implying that Au deposition occurred simultaneously with that of uraninite (Hills 1973). The distribution of Pd is very similar to that of Au (Wilde et al. 1989a), implying contemporaneous deposition of all three elements. Minor chalcopyrite and galena, but no Au, occur with dolomite and quartz in veinlets that postdate the uraninite.

Gold is also present within most of the deposits in the South Alligator Valley and two distinct types of mineralisation have been recognised at Coronation Hill (Mernagh et al. 1994). The first is U–Au–PGE ore, found at or below the unconformity beneath the Kombolgie Formation and generally restricted to conglomerates containing carbonaceous clasts and chloritic alteration zones in quartz-feldspar porphyry. Visible to microscopic grains of Au occur with the U ore, which consists of disseminated and patchy uraninite. The second style is Au–PGE ore with very low U content, which is also confined to the stratigraphic units below the unconformity, but otherwise appears to have no lithological control. Au–PGE ore is not closely correlated with U or pyrite and the overall sulphide content is low, with minor pyrite, pyrrhotite, sphalerite, chalcopyrite, and galena (Mernagh et al. 1994).

Chemical controls on mineralisation

Fluid inclusion studies in the Alligator Rivers uranium field (Ypma & Fuzikawa 1980, Wilde et al. 1989b) were restricted to inclusions in pre-ore and late-stage quartz and carbonate, but a fluid-inclusion study of the Coronation Hill deposit in the South Alligator Valley used quartz and carbonate that were intimately associated with the main stage of mineralisation (Mernagh et al. 1994). All these studies produced similar results, which showed that the ore-bearing fluid was initially a highly oxidised, acidic, calcium-rich brine and that mineralisation occurred at temperatures greater than 100°C, but less than 250°C. At these conditions, transport of Au and PGE would involve mainly chloride complexes, whereas U may be transported as the oxychloride species and, thus, all species could be transported in the same fluid. Oxygen isotope and mineralogical evidence (Binns et al. 1980, Ypma & Fuzikawa 1980, Ewers et al. 1984, Mernagh et al. 1994) suggests that the ore fluid originated as saline ground water which travelled down subvertical faults before reacting with the feldspathic and reduced lithologies below the neutral sandstone of the Kombolgie Formation.

Thermodynamic calculations (Wilde et al. 1989b, Jaireth 1992, Mernagh et al. 1994, Komninou & Sverjensky 1996) indicate that mineralisation may occur by reduction of the oxidised fluid and/or by an increase in pH. Chemical modelling of the reaction of the ore-bearing fluid with potash feldspar (Mernagh et al. 1994) results in a moderate decrease in fO_2, an increase in pH from below 4 to 5.1, and precipitation of Au, Pt, and Pd with little or no U. A greater decrease in fO_2 and/or an increase in pH is needed to precipitate the U ± Au ± PGE ore and this may result from either the direct interaction with highly carbonaceous or ferruginous units or from mixing with reduced fluids originating from below the unconformity beneath the Kombolgie Formation. This model explains the observed wider distribution of the Au–PGE-only ore across a number of feldspathic lithologies and the restriction of the U–Au–PGE ore to carbonaceous–chloritic host rocks.

Geophysical surveys

Airborne and ground radiometric surveys have been the principal exploration tool for U deposits in the Pine Creek Inlier (Ryan 1972, Tipper & Lawrence 1972, Rowntree & Mosher 1981). Self potential geophysical surveys have also been successfully used in the region. This technique delineates carbonaceous shales (a potential host rock for mineralisation), but, unfortunately, does not distinguish between mineralised and barren shales. Ground observations have shown that alteration zones surrounding mineralisation in the South Alligator Valley have slightly elevated U, but are strongly depleted in Th (Wyborn et al. 1994). Airborne gamma-ray spectrometric data are useful for identifying alteration zones associated with the loss or gain of Th. Wyborn et al. (1994) found that the most useful gamma-ray spectrometric image for defining areas of potential mineralisation in the South Alligator Valley was the ratio U^2/Th, which highlights the alteration zones associated with areas of mineralisation. Unfortunately, this ratio may also highlight areas that have naturally high levels of K and U, but no Th (e.g. black shales and black soil plains). However, by using the ratio U^2/K, these pseudo anomalies can be eliminated. Note also that, as a consequence of Th depletion in the alteration zone, there may be enrichment of Th at higher structural levels, particularly near faults, and this may indicate concealed mineralisation at depth, although care must be taken as laterite can also have anomalously high Th contents.

As mentioned above, hematite is present in many of the alteration zones surrounding the mineral deposits. These hematite zones have low magnetic susceptibilities and are visible in the airborne data as magnetic lows (e.g. Wyborn et al. 1994). The hematite in the alteration zones surrounding mineralisation has formed from the conversion of magnetite by the passage of oxidising fluids and, thus, the airborne magnetic data can be used to map the circulation of these oxidised fluids in the Pine Creek Inlier.

Geochemical surveys

Geochemical surveys indicate that U is the best geochemical pathfinder and multi-element surveys have only been of secondary importance (Binns et al. 1980). Stream-sediment surveys (Wyborn et al. 1994) have shown that other trace elements do not define a unique pattern, as results are influenced by the dominant lithology in the drainage basin. High Ni and Cr were recorded in streams in the vicinity of altered mafic rocks, whilst Mn was high in prospects draining ferruginous shales. Ba was high where the host rocks included feldspathic rock types such as arkose and quartz feldspar porphyry. U was high in areas draining carbonaceous shales and, as with gamma-ray spectrometry, U anomalies associated with mineralisation could be distinguished from areas of high natural background by the U^2/Th ratio.

Rock-chip surveys carried out in the South Alligator Valley (Wyborn et al. 1994) have shown that the majority of U deposits have elevated Au, Pt and Pd. These deposits also showed enrichments in As, Cu, La, Ce, Nd, Sr, Zr, Cr, Ni, Ba, Mn, and P_2O_5. Ypma & Fuzikawa (1980) considered that inclusion fluids with high concentrations of Mg, Ca and Na chlorides were indicators of proximity to U mineralisation. This was based on their observations that fluid inclusions in and around orebodies contained concentrated saline brines with as much as 5–10 wt.% $MgCl_2$, 20–30 wt.% $CaCl_2$, and 10–20 wt.% NaCl.

Conclusions

This style of U ± Au ± PGE mineralisation is best developed in reduced basement lithologies, near an unconformity and has thus become known as 'unconformity-related' mineralisation. It may form when oxidised fluids capable of simultaneously transporting U, Au and PGE are reduced and/or undergo an increase in pH. Mineralisation occurs when the ore-bearing fluid reacts with rocks containing reductants or mixes with more reduced fluids, either within the cover sequence, at the unconformity or deeper in the basement sequence.

A thick, chemically neutral to oxidised cover sequence is required to act as a reservoir for the oxidised, metal-bearing brines and to act as a thermal blanket to allow the fluids to reach temperatures of >100°C. These metal-rich brines typically descend along faults until they interact with either the rocks or fluids in the cover or basement sequences. If the ore-bearing fluids interact with feldspathic or calcareous rocks, then precipitation of Au + PGE ore may occur with most of the U remaining in solution. A greater increase in the pH and/or reduction of the fluid is required to precipitate the U and any remaining Au and PGE. This usually occurs when the ore-bearing fluids reach the unconformity and react with carbonaceous or ferrous iron-rich rocks, or mix with reduced fluids derived from deeper in the basement.

These 'unconformity-related' deposits are restricted to specific geological environments, and regional area selection criteria for unconformity-style U ± Au ± PGE deposits should focus on the following:

- major dilatant structures and zones of brecciation within a strike-slip fault system;
- a thick, neutral to oxidised cover sequence;
- adjacent lithologies with contrasting chemical oxidation potentials and separated by either an unconformity or a fault;
- evidence of large scale alteration zones and the circulation of highly oxidised fluids.

Note that feldspar-rich lithologies which do not contain significant amounts of reductants improve the chances of finding Au + PGE mineralisation without U. Alteration zones may extend for over 1 km from the deposit and in airborne magnetic surveys the mineralised zones appear as magnetic lows, whilst for gamma-ray spectrometry, the ratios of U^2/Th or U^2/K better define the areas of mineralisation.

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