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TABLES

SANDSTONE DEPOSITS

The known sandstone deposits of uranium in Australia are located in South Australia, north-west Queensland, Northern Territory and Western Australia. The uranium fields and basins containing these deposits are the Frome Embayment field, Eucla Basin, Westmoreland–Pandanus Creek field, Amadeus Basin, Ngalia Basin, Gunbarrel Basin, Carnarvon Basin and Canning Basin.

FROME EMBAYMENT URANIUM FIELD

Oilmin NL and Transoil NL explored the Proterozoic rocks of the North Flinders Ranges in South Australia for uranium during the mid-1960s. In 1968, together with Petromin NL, they began an assessment of the uranium potential of the Tertiary sediments to the east, which have been derived from the uranium-rich metamorphics in the Mount Painter area (Fig. 26). Rotary mud drilling began the following year and the first rocks to be tested were alluvial fans flanking the Flinders Ranges. Early drilling was difficult because of large granite blocks in scree in the upper part of the section. No significant radioactivity was found in the sediments close to the ranges. Holes drilled further east intersected low-grade mineralisation in the vicinity of the Beverley deposit (Fig. 26). Indications of uranium mineralisation at Beverley were first detected in 1969 by the Oilmin–Transoil–Petromin group of companies. The first hole to intersect economic-grade mineralisation at the Beverley deposit was drilled in 1970. By then, 10 000 m of drilling had been completed (Haynes, 1975). In June 1972, Western Nuclear Australia Ltd signed a joint-venture agreement with the Oilmin–Transoil–Petromin Group to fund exploration and development drilling at Beverley. Western Nuclear Australia Ltd later earned a 50% equity in the project. The subsequent evaluation and development of the Beverley in situ leach (ISL) operation are described later in this chapter, in ‘Beverley deposit’.

Following the Beverley discovery, there was a rapid increase in uranium exploration throughout the Frome Embayment by many exploration companies (Yates & Randell, 1994). Sedimentary Uranium NL explored early Tertiary palaeochannels in the southern part of the embayment, and discovered the Yarramba deposit in 1970 and the East Kalkaroo deposit in 1971 (Sedimentary Uranium NL, 1971; Brunt, 1978; Yates & Randell, 1994). The Yarramba deposit was the first discovery of significant mineralisation in the Yarramba Palaeochannel.

Reconnaissance drilling during 1971 and 1972 by Carpentaria Exploration Company (CEC) intersected minor uranium mineralisation in Tertiary sandstones in the southern part of the Yarramba palaeochannel. A joint venture was subsequently formed by CEC, Mines Administration Pty Ltd (Minad) and Teton Exploration Drilling Co. Pty Ltd (Teton). During 1972, drilling carried out by the joint venture intersected mineralisation in the deposit now known as Honeymoon. Extensive exploration drilling and close spaced resource drilling at Honeymoon continued through to 1981. A total of 286 holes were drilled to define the Honeymoon deposit (Curtis, Brunt & Binks, 1990). Development of the Honeymoon project is described in a later section of this chapter. Reconnaissance resistivity traversing was also used to locate buried palaeochannels. The stratigraphy and possible mineralisation in these channels were then rotary drilled and gamma ray logged (Brunt, 1978).

From 1978 to 1982, Marathon Petroleum explored for uranium in the Oban Bore–Berber Dam area, 65 km north of Honeymoon. Zones of low-grade mineralisation were discovered at the Oban prospect (Fig. 26). A total of 195 holes were drilled into this palaeochannel. Paladin Resources NL carried out later work in this area.

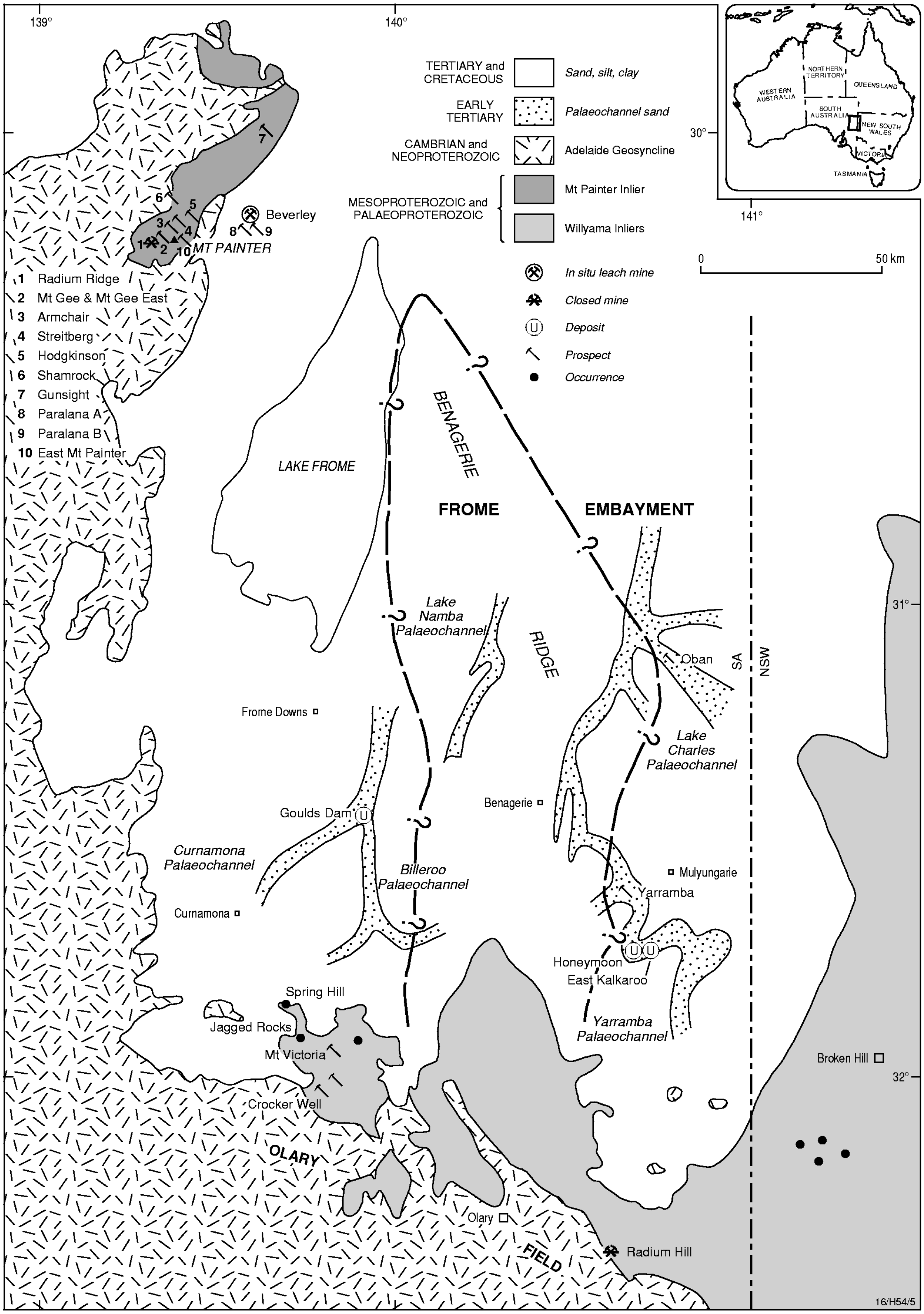

Figure 26. Regional geology of the Frome Embayment and environs showing Tertiary palaeochannels and uranium deposits, prospects and minor occurrences (locations of palaeochannels after Curtis, Brunt & Binks, 1990)

In 1983, the Commonwealth Government introduced the ‘Three mines’ policy. From the mid-1980s through to 1995 there was virtually no uranium exploration in the Frome Embayment.

After 1996 there was a marked increase in uranium exploration in this area due to the 1996 removal of the ‘Three mines’ policy, and improvements in ISL technologies for uranium mining, mainly in the United States. Paladin Resources NL, in joint venture with a number of exploration companies, began exploration within the palaeochannels in the southern part of the Frome Embayment (Borschoff, 1998). Southern Cross Resources Australia Pty Ltd purchased the Honeymoon project in 1997 and completed in situ leach trials.

The **Paralana** prospects (Fig. 26), 8 km south of the Beverley deposit, are in a geological setting similar to that at Beverley and are held by Heathgate Resources Pty Ltd. In 2000, Heathgate Resources Pty Ltd, in joint venture with Giralia Resources NL, commenced exploration in three exploration licences over these prospects.

Regional geological setting

The regional geology of the Frome Embayment has been described by Callen (1975, 1981, 1990), Brunt (1978) and Callen, Alley and Greenwood (1995). The Frome Embayment is a lobe on the southern part of the Callabonna Sub-basin which is the south-western portion of the Lake Eyre Basin (Callen & others, 1995). The Callabonna Sub-basin comprises Tertiary shallow-water sediments. The Flinders, Olary and Barrier Ranges flanking the embayment, consist mainly of Precambrian and Cambrian metamorphic and sedimentary rocks which contain many small uranium deposits and widespread disseminated uranium mineralisation.

During the early Tertiary, well-sorted sand (Eyre Formation) was deposited as a thin, laterally continuous horizon covering the full width of the Sub-basin in the north. In the south, the Eyre Formation equivalents — angular, poorly sorted, fluvial sand and interbedded clay and silt — were deposited in major stream channels of restricted areal extent (Brunt, 1978). The channels were incised into Precambrian basement and marine clay of the Late Cretaceous Marree Subgroup.

Clay, sand and dolomite of the Namba Formation (Miocene) formed a continuous sequence disconformably overlying the channel sediments (Callen & Tedford, 1976). A thicker sequence of the Namba Formation accumulated closer to the Flinders Ranges to form the small Poontana Sub-basin.

The Honeymoon, East Kalkaroo, Yarramba and Goulds Dam deposits are in palaeochannel sand of the Eyre Formation (Palaeocene–Eocene), whereas the Beverley deposit is in sand of the overlying Namba Formation (Miocene) (Table 16). The palaeochannels in the southern part of the Frome Embayment flank a structural high in the underlying basement, the Benagerie Ridge.

In describing the events that led to the formation of the sedimentary uranium deposits, Brunt (1978) stated that the Tertiary sand was derived from Precambrian metamorphics and granitic rocks in the surrounding uplands and was deposited in the channels together with abundant plant matter. Shortly after deposition, anaerobic decay of the organic matter in the water-saturated sand produced a reducing alkaline environment. Uranium contained in mineral detritus and rock fragments was deposited together with the channel sands.

Following the fluvial sedimentation, clay and silt were deposited, and formed a seal on top of the channel hydrologic system. Oxidising groundwater, moving slowly through the channel sands, leached uranium and re-precipitated it down-gradient at the redox interface. Roll-front bodies formed at the redox interface, particularly where migration of the groundwater was impeded by reduced permeability and

Table 16. Simplified regional stratigraphy of the Frome Embayment (Drexel & Preiss, 1995)

		Age	Lithology	Average thickness (m)	Uranium deposits
Callabonna Sub-basin (Lake Eyre Basin)	Coonarbine, Eurinilla, Millyera Formation & other units	Pleistocene to Recent	Soil, dune sand, sand, clay, gravel, calcrete, gypcrete	Variable, thin	
	Willawortina Formation	Late Miocene to Early Pleistocene	Clay, sand, sandy conglomerate and dolomite	0–150	
	Namba Formation	Miocene	Silt & clay, with minor sand, limestone, dolomite	200	Beverley
	DISCONFORMITY				
	Eyre Formation	Early Palaeocene to Late Eocene	Sand & sandstone, some pebble beds	10–75	Honeymoon, East Kalkaroo, Yarramba, Goulds Dam
UNCONFORMITY					
Eromanga Basin	Maree Subgroup	Cretaceous	Shale and siltstone	150–275	
	Cadna-Owie Formation & Algebuckina Sandstone	Jurassic to Cretaceous	Shale, sand, silt and boulder lenses	Variable	

thinning of sand units towards the banks of the channel. The passage of these groundwaters caused oxidation of pyrite and organic matter, leaving orange- and red-coloured iron oxide staining of the sands.

Alternatively uranium was introduced in solution rather than in mineral detritus and rock fragments, and was transported through the palaeochannel to be precipitated in favourable reducing environments.

Beverley deposit

History of development

The Beverley uranium deposit lies in the north-western part of the Frome Embayment (Fig. 26). Exploration by the Oilmin–Transoil–Petromin Group in Tertiary sediments of the western Frome Embayment resulted in the discovery of the Beverley deposit in 1969. Intensive drilling to define the resources was carried out during 1971–72 by a joint venture between the Oilmin–Transoil–Petromin Group and Western Nuclear Inc. This was followed by metallurgical and engineering studies to investigate the feasibility of mining the deposit by conventional open pit operations. However, Commonwealth Government uranium policy and market influences caused the project to be wound back and shelved in June 1974.

In 1981, the South Australian Uranium Corporation acquired the deposit and began technical and environmental studies to investigate the amenability of the deposit to mining by in situ leach (ISL) technology, which was relatively new at the time. A draft Environmental Impact Statement (EIS) for the proposed ISL operations was released, but introduction of the Commonwealth Government 'Three mines' policy in 1983, together with declining uranium market prices, led to the project being shelved again in mid-1985.

Heathgate Resources Pty Ltd acquired the property in 1990 and initiated new investigations of ISL mining using latest technologies developed from recent US operating experience. Following removal of the 'Three mines' policy in 1996, in situ leach field trials were carried out in 1998 aimed at testing the viability of these extraction techniques. The draft EIS for the proposed development, which was released in June 1998, was assessed jointly by the Commonwealth and South Australian Governments. The Supplement (Response Document) to the EIS was released in September 1998. In April 1999, the company received Commonwealth and State environmental clearances to develop Beverley. Construction of the ISL plant and wellfields was completed and production of concentrates commenced in November 2000. Annual production is planned to be 1000 t U_3O_8.

Geology

The deposit occurs in uncemented, partly consolidated sediments of the Namba Formation (Upper Tertiary), which were deposited in a confined palaeochannel sequence in a shallow-water terrestrial environment. On a regional basis, the Namba Formation is subdivided into the Upper and Lower Units (Callen & Tedford, 1976). The stratigraphic correlation of the sedimentary units in the vicinity of the orebody (Heathgate, 1998) with the regional subdivision of the Namba Formation is shown in Table 17.

Table 17. Stratigraphic nomenclature of the Beverley deposit

Nomenclature by Callen & Tedford (1976)		**Nomenclature by Heathgate (1998)**	**Lithology**	**Mineralisation**
Namba Formation	Upper Unit	Beverley Clay	Clay	
		Beverley Sands — Upper	Clay, sand	Beverley U deposit
		Beverley Sands — Lower	Sand, clay	
	Lower Unit	Alpha Mudstone	Clay	

The Alpha Mudstone is a dark brown to black clay unit containing black organic matter formed by the decay of plant and wood fragments. It is approximately 100 m thick below the orebody. The palaeosurface on the Alpha Mudstone has several channels which trend south-easterly (Figs 27 and 28) (Heathgate, 1998). These three palaeochannels constitute the Beverley aquifer.

The Beverley Sands are uncemented fine- to medium-grained sands with inter-bedded clays and silts. These sediments were deposited in a fluvial environment.

The Beverley Clay is a predominantly clay sequence which overlies the mineralised sands. This clay sequence forms an impermeable barrier which isolates the mineralised sands (Beverley aquifer) from the overlying Willawortina Formation and its aquifers. The Willawortina Formation comprises interlaminated clays, sands and gravels.

The Poontana Fault zone is a near-vertical fault zone which lies immediately to the west of the orebody. Vertical movement along the fault zone appears to have taken place during sedimentation and this appears to have controlled the distribution of the sediments and the palaeochannels.

Mineralisation

Uranium mineralisation forms three lenticular zones, designated north, central and south ore zones. The north and central ore zones are within the central channel while the south ore zone is situated in the south channel. Mineralisation is mainly within the Beverley Sands and the combined thickness of the mineralised sand is typically 20–30 m. Minor mineralisation also occurs in the Beverley Clay and the

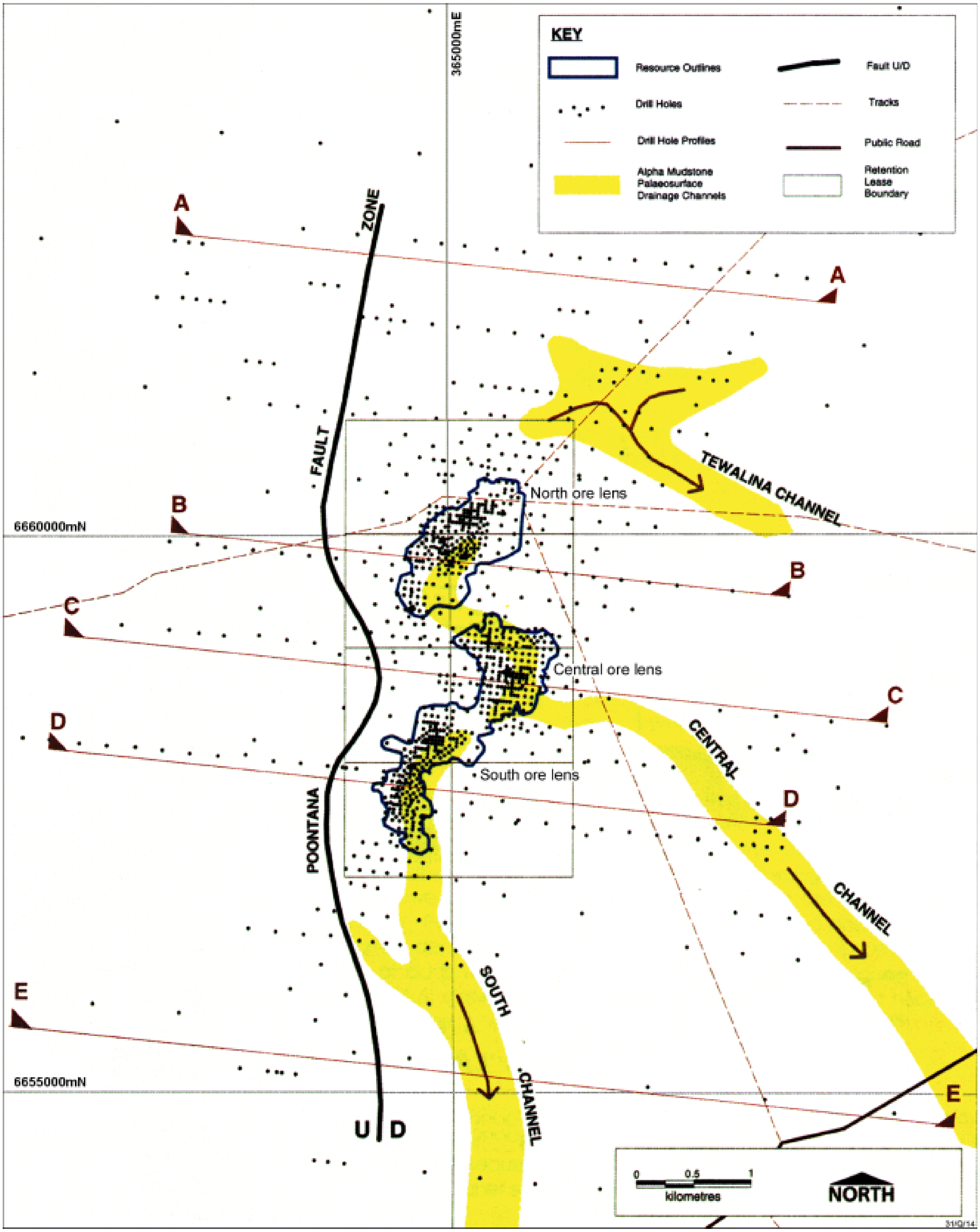

Figure 27. Plan showing Beverley ore lenses, palaeochannels and Poontana fault zone (after Heathgate, 1998)

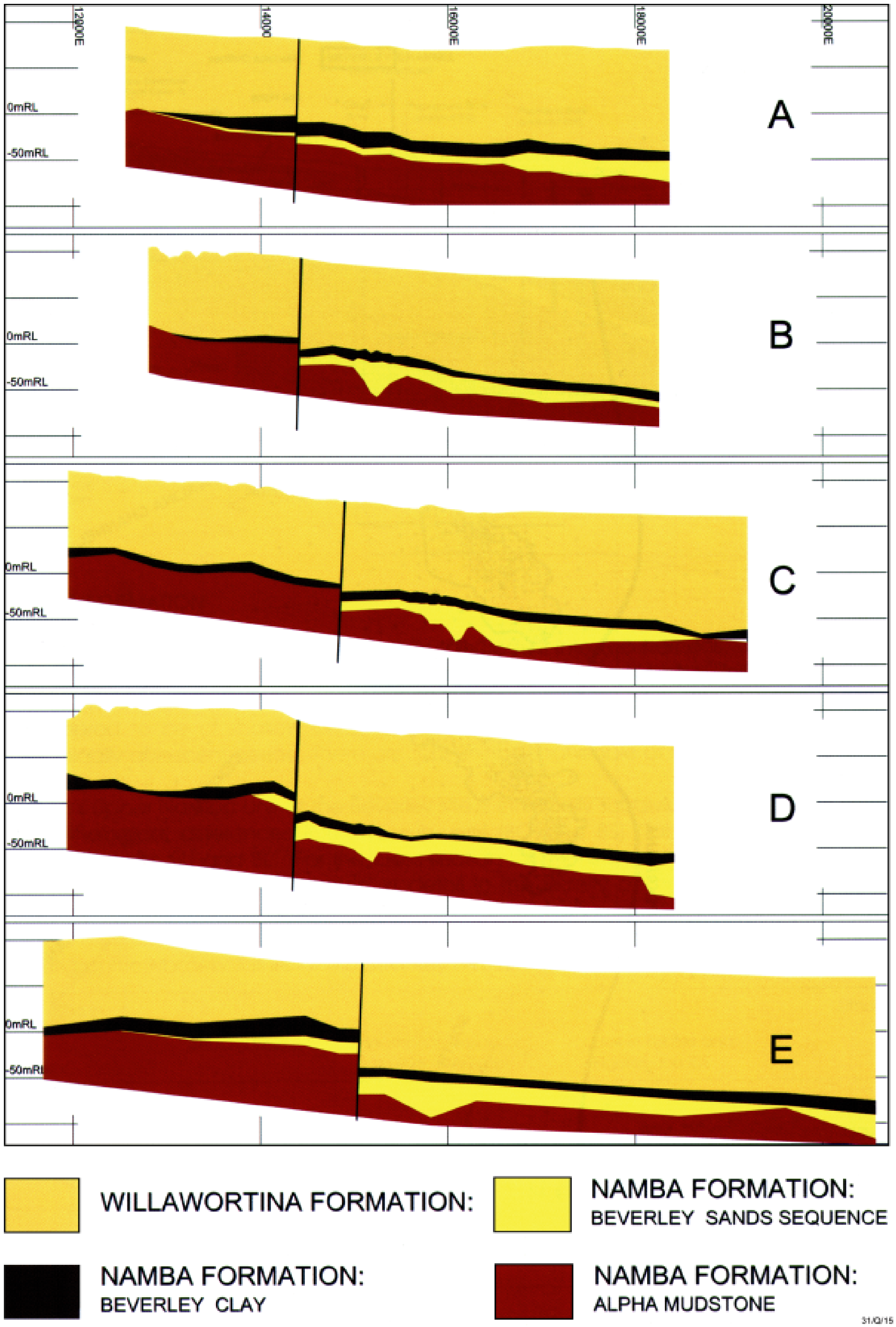

Figure 28. Cross-section through the Beverley aquifer (after Heathgate, 1998)

uppermost sections of the Alpha Mudstone, but this mineralisation cannot be recovered by in situ leaching and has been excluded from the resource estimates (Heathgate, 1998).

Mineralisation occurs at an average depth below surface of 107 m, but depths range from 83 m at the north ore lens to 145 m at the south ore lens.

Uranium is present mainly as coffinite (which forms coatings on sand grains) together with some uraninite. The host sands are dominantly quartz, various clays, minor feldspar and traces of gypsum. Organic carbon ranges from <0.05% to 0.5% in grey sands and up to 2% in a few samples. Sulphides (pyrite and marcasite) are generally not present other than in trace amounts (Heathgate, 1998).

The Beverley ore zones are tabular in shape. There appears to be no evidence for mobilisation of uranium by oxidising groundwaters. To explain the formation of the orebody, Heathgate (1998) considered that late secondary processes remobilised uranium into the present shape, and that the groundwaters and host sediments were later re-reduced.

Uranium in the Beverley deposit was derived from erosion of Proterozoic basement rocks in the Mount Painter uranium field which host small uranium deposits in hematite-rich breccias (see 'Mount Painter uranium field' in the 'Breccia Complex Deposits' chapter above).

Resources

Heathgate calculated the resources for the Beverley deposit using drill hole data from more than 1000 holes that have been drilled into the deposit since the early 1970s. The total in-place resources mineable by in situ leaching were estimated to be 12 Mt ore with average grade 0.18% U_3O_8, which represents 21 000 t U_3O_8 (Heathgate, 1998). The parameters were: cut-off grade of 0.03% U_3O_8, minimum ore thickness of 0.5 m and a dry bulk density of 1.8 t/m^3.

Complex disequilibrium relationships and shortcomings in sampling techniques for the purpose of in situ leaching limit to some extent the degree of confidence that can be placed on the grade, quantity and exact location of potentially economic mineralisation. Accordingly, Heathgate has discounted the resources and has reported that the total in-place resources are 16 300 t U_3O_8. Total resources recoverable by ISL mining are estimated to be a minimum of 10 600 t U_3O_8 (Heathgate, 1998).

In situ leach operations

For the ISL operations at Beverley, the uranium is dissolved in situ by sulphuric acid in low concentrations, together with oxygen (or hydrogen peroxide), added to the groundwater. In the processing plant, resin-type ion-exchange techniques are used to recover the uranium from the leachates.

Acid leach was selected because the results from the field leach trials and past laboratory testing of core from Beverley showed that acid leach gives faster and more complete extraction of uranium than alkaline leach (Heathgate, 1997). Low carbonate levels within the aquifer sands and the groundwater allow the use of an acid leach.

Hydrogeology of the Beverley aquifer

Groundwater in the mineralised zone is saline, with total dissolved solids in the range 3000–12 000 mg/L. It contains naturally occurring uranium and radium well in excess of drinking water limits, so is unsuitable as potable water and unsuitable for agriculture or stock watering.

Liquid wastes from the ISL operations are disposed of by re-injection into the Beverley aquifer zone in areas already mined out. Liquid wastes come from several sources: a mining solution bleed at the plant, spent solutions from the uranium precipitation process; and washdown water and filter cleaning water. For environmental approvals to dispose of liquid waste into the Beverley aquifer, it has been necessary for the company to show that there is no hydraulic connection between the Beverley aquifer and the surrounding aquifers.

Sediments that confine the mineralised zone

The Alpha Mudstone (which is stratigraphically below the Beverley aquifer sands) and the Beverley Clay (above the Beverley aquifer sands) both provide a high degree of confinement to the mineralised sands (Heathgate, 1998) (Fig. 29). They are thick, highly plastic clays which are continuous over areas much larger than the extent of the mineralisation. The Beverley aquifer is separated stratigraphically from the Great Artesian Basin aquifer by approximately 100 m of dense, highly plastic clays of the Alpha Mudstone (Gatehouse, 1997; Heathgate, 1997).

Within the Beverley Sands there are numerous clay horizons which range from thin laminae to thick beds. Collectively these layers provide a high degree of confinement particularly at the lateral margins of the channel (Heathgate, 1998). Outside the channels, the Beverley sand unit is represented by a thin (<5 m) sand sheet, or by thinly interbedded silts and sands typical of stream overbank deposits. The sand unit lenses out against local highs on the underlying Alpha Mudstone surface. Results from pumping tests (Coffey, 1973; Heathgate, 1998) showed that low permeable zones must be present at the edges of the mineralised sand zones.

Discharge from the Beverley aquifer is believed to be virtually zero for two reasons (Heathgate, 1998):

- the hydraulic gradient along the Beverley channel is virtually zero (i.e. there is virtually no lateral flow); and
- vertical hydraulic gradients are directed towards the channel sands from above (Willawortina) and below (very large gradient due to the Great Artesian Basin aquifer).

Lisdon Associates (1999) concluded that the fully bounded nature of the aquifer channel makes it an ideal location for the disposal and long-term storage of liquid wastes, especially if injection and storage can be achieved with minimal change to the distribution of pressure within the system. An independent assessment of the Beverley aquifer by the Bureau of Rural Sciences (Habermehl, 1999) confirmed these findings and stated, 'The Beverley Sand aquifer is sealed from the Cadna-Owie Formation aquifer of the Great Artesian Basin and from the overlying Willawortina Formation aquifers'.

As a result of these findings, Heathgate was granted approvals to dispose of liquid wastes by re-injection into the northern mineralised zone of the Beverley Sand aquifer.

Honeymoon deposit

History of development

Following the discovery of the Honeymoon deposit in 1972, a major drilling program was carried out to delineate the deposit, continuing through to 1976. A feasibility study completed in 1976 showed that it would be uneconomic to mine the deposit by open cut or underground methods.

A series of in situ leach (ISL) trials was carried out at Honeymoon in 1977 and 1979 using the ISL mining technology that was being developed in the United States at that time. These trials, together with laboratory tests by the Australian Mineral Development Laboratories, confirmed that the deposit would be amenable to ISL mining.

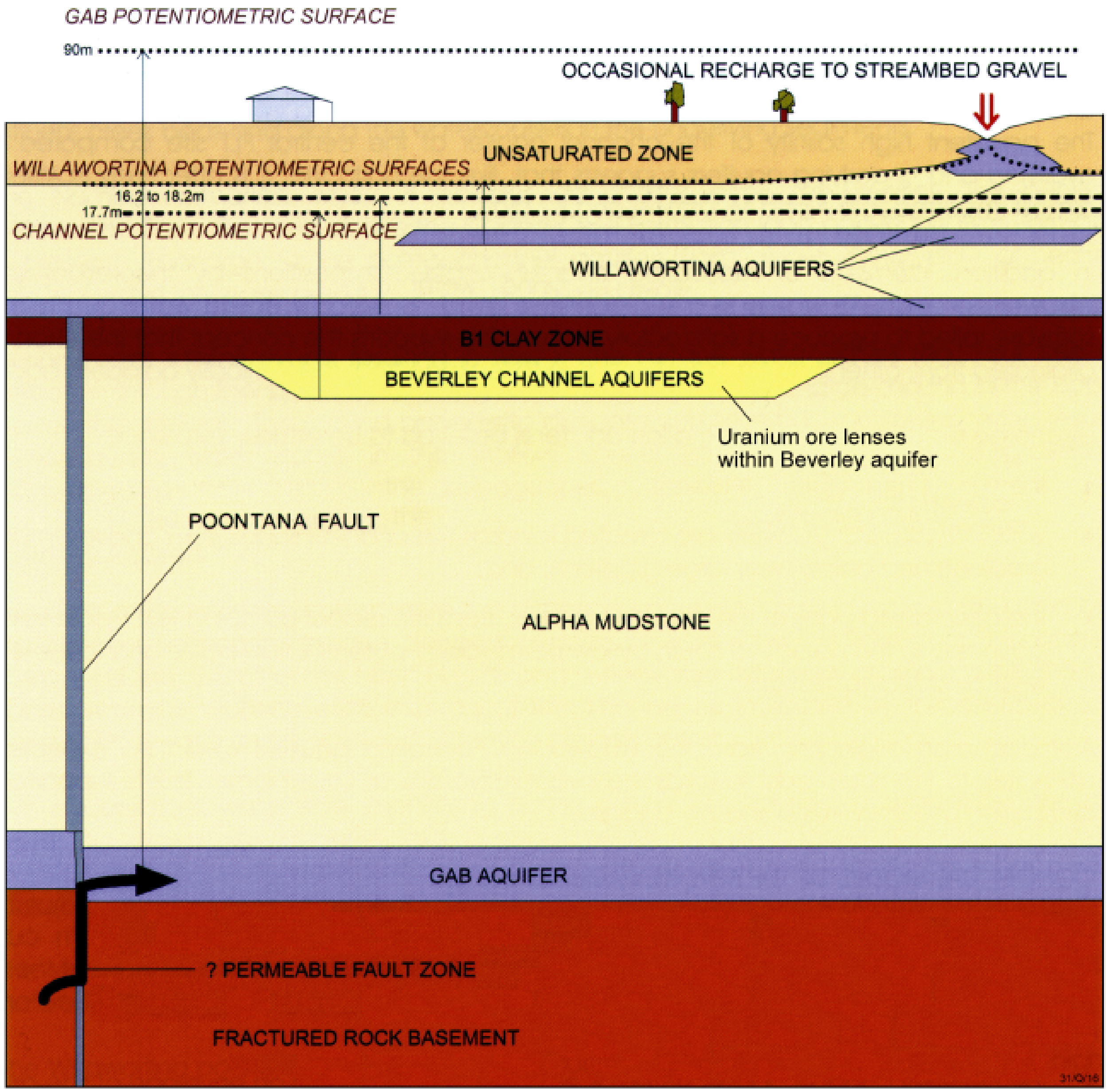

Figure 29. Hydrogeology model in the vicinity of the Beverley palaeochannel (after Heathgate, 1998); GAB stands for Great Artesian Basin; B1 Clay stands for Beverley Clay

A final EIS for the Honeymoon project was submitted in March 1981 (Mines Administration Pty Ltd, 1981). Government approval to proceed to the next stage of development of the project was granted, and in 1982 Minad constructed a 25 L/s solvent extraction ISL processing plant at Honeymoon. In addition, a pilot wellfield of three five-spot leach patterns and monitor wells was completed. Before the pilot wellfield and processing plant could be commissioned there was a change of Government in South Australia and shortly afterwards a change in Commonwealth Government. In March 1983 the grant of a mining lease was refused; the project was placed under care-and-maintenance in June 1983.

In May 1997, Southern Cross Resources acquired the Honeymoon and East Kalkaroo deposits (Ackland, 1997; Bush, 1998). The company also purchased the Retention Leases covering the Goulds Dam deposit. The processing plant was refurbished and the pilot wellfield was re-established. New wellfields were also developed. In addition, new camp and laboratory facilities were constructed. In situ leach trials commenced in 1999 and uranium peroxide concentrate ($UO_4.2H_2O$) was successfully recovered at the plant. Sulphuric acid and an oxidant (oxygen, hydrogen peroxide) were used to mobilise the uranium, and concentrates were recovered in the plant using solvent extraction. The final EIS for the project, which was released in December 2000, is being assessed jointly by the South Australian and Commonwealth Governments.

Geology

The Honeymoon deposit is in the southern portion of the Frome Embayment. In this region, Precambrian basement rocks are unconformably overlain by sediments of the Cainozoic Callabonna Sub-basin. The main sediments are fluviatile sands of the Eocene Eyre Formation which hosts the Honeymoon, East Kalkaroo and Goulds Dam uranium deposits. These sands were deposited in a number of palaeochannels eroded into the underlying basement of Precambrian metasediments (Fig. 26). Eyre Formation sediments are disconformably overlain by Miocene clay-rich sediments of the Namba Formation.

The Honeymoon deposit occurs along the outer margin of a sharp bend in the Yarramba Palaeochannel (Fig. 26). Mineralisation is in porous, coarse-grained basal sands of the Eyre Formation, which contain pyrite and organic carbon. The Eocene palaeochannel sediments are uncemented sands and clays, and the sequence has been subdivided into three units. Each unit comprises sand with interbedded clays and a thick clay unit at the top (Fig. 30). The three sand units are referred to as basal sand, middle sand and upper sand, and are separated by the middle clay, upper clay and top clay (Southern Cross, 2000).

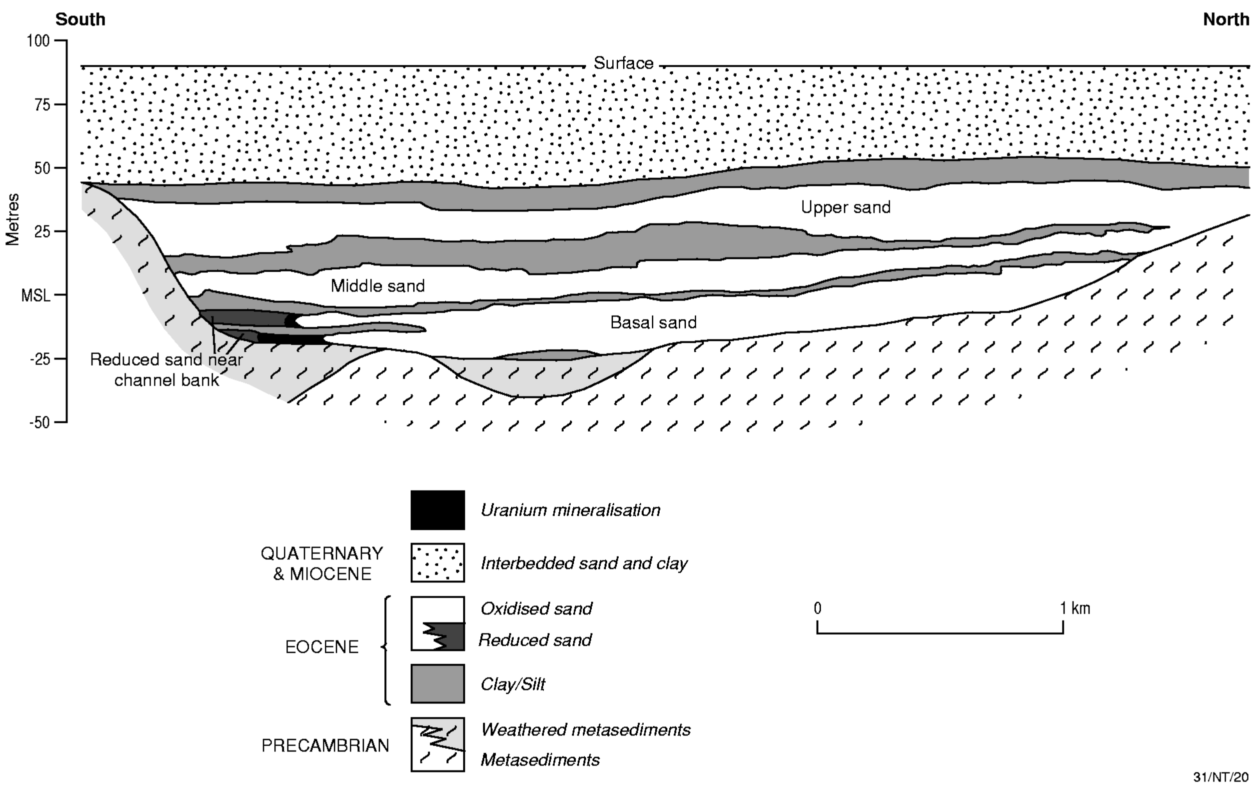

Figure 30. Diagrammatic cross-section through the Yarramba Palaeochannel and Honeymoon deposit (after Southern Cross, 2000); MSL stands for mean sea level

The palaeochannel sediments are predominantly orange- to yellow-coloured oxidised sands. Where the permeability is low, the sands are in their initial reduced state and are grey in colour with variable amounts of pyrite and organic matter. Mineralisation occurs along a redox boundary at the lateral margins of the palaeochannel, where the basal sands are confined between the overlying clay and the side of the palaeochannel (Curtis & others, 1990; Southern Cross, 2000) (Fig. 30).

The deposit occurs at a depth of 110 m below surface, extends for more than 1500 m along the channel margin, is up to 400 m wide and averages 4.3 m thick. The ore consists of microscopic coffinite associated with humic and pyritic material along the redox boundary.

Groundwaters within the palaeochannel sands are very saline with total dissolved solids ranging from 10 000 to 19 000 mg/L. The basal sands aquifer has very high salinities: 16 000 to 19 000 mg/L total dissolved solids (Southern Cross, 2000). Waters in the basal and middle sands are unsuitable for stock watering. Waters in the upper sands, although generally unsuitable, are used intermittently for stock watering in areas to the north of the deposit.

Southern Cross has estimated the mineral resources that are amenable to in situ leaching (Table 18). The estimate was calculated from equivalent uranium grades measured by down-hole gamma-ray probes. The following parameters were used for this estimate: minimum ore thickness 0.4 m, minimum grade 0.04% eU_3O_8 (equivalent U_3O_8 from radiometric measurements), minimum accumulation (grade x thickness) 0.016 m% U_3O_8, and maximum thickness of included dilution 1.2 m. In situ leaching will recover approximately 70% of this amount (Southern Cross, 2000). The resources, as reported, do not have a resource classification attributed to them because Southern Cross considers that the *Australasian Code for Reporting of Mineral Resources and Ore Reserves* (JORC, 1999) does not contain categories for resources recoverable by in situ leach methods. The company has prepared a submission addressing these concerns, for consideration by the Joint Ore Reserves Committee.

Table 18. Resources amenable to in situ leaching in the Honeymoon, East Kalkaroo and Goulds Dam (Billeroo West) deposits (Southern Cross, 2000)

	Area (ha)	Specific gravity	Grade x thickness (average) (m%)	eU_3O_8 (t)
Honeymoon	29.0	1.9	0.71	3 900
East Kalkaroo	123.0	1.9	0.18	4 000
Goulds Dam (Billeroo West)	815.0	1.8	0.12	17 600

East Kalkaroo deposit

The East Kalkaroo deposit, 2.5 km east of Honeymoon, occurs along the outer margin of the same bend in the Yarramba Palaeochannel. A basement ridge in the channel separates the East Kalkaroo and Honeymoon deposits although the deposits occur along the same broad redox boundary. Low-grade mineralisation occurs in this separation zone. The East Kalkaroo deposit extends for approximately 2 km along the palaeochannel, averages 250 m wide and is in the basal sand unit. The redox boundary is complex, with a broad transition from fully oxidised to reduced sediments (Curtis & others, 1990). Table 18 lists the resources at East Kalkaroo deposit that are amenable to in situ leaching. Approximately 70% of these resources will be recovered by in situ leaching.

Yarramba deposit

The Yarramba deposit is in the Yarramba Palaeochannel, 12 km north of Honeymoon. Mineralisation is in the basal and middle sands, and appears to be related to a poorly defined redox interface that formed behind a rock bar cutting across the channel (Southern Cross, 2000). Uranium is concentrated along clay–sand interfaces and is most abundant in the middle sand (Curtis & others, 1990). Resource estimates have not been published.

Goulds Dam deposit (Billeroo West area)

The Goulds Dam deposit is within the Billeroo Palaeochannel and is associated with a redox interface near the confluence of the Curnamona Palaeochannel and the Billeroo Palaeochannel (Fig. 26). These channels contain Tertiary sands and clays of the Eyre Formation and have been subdivided into lower, middle and upper members, similar to the Yarramba Palaeochannel. Mineralisation is confined to sands of the lower member (Curtis & others, 1990). In 1997, Southern Cross Resources acquired the Billeroo West Retention Leases from Carpentaria Exploration Company. These cover the deposit and approximately 8 km of the Billeroo Palaeochannel. A drilling program was carried out in 1997 and 1998 to further define the resources. The resources amenable to in situ leaching are shown in Table 18. Approximately 70% of this resource could be recovered by in situ leaching.

Oban deposit

The Oban deposit, 65 km north of Honeymoon, is along the northern margins of the Lake Charles Palaeochannel. The palaeochannel is 70–80 m below surface and contains 20–30 m of Eyre Formation sands. Mineralisation is associated with a restricted redox interface near the base of the channel (Curtis & others, 1990).

EUCLA BASIN (EYRE PENINSULA REGION)

Uranium occurs in Eocene palaeochannel sediments in the Eyre Peninsula region (SA). These are basal sediments of the Eucla Basin and they overlie Archaean and Proterozoic granites, gneiss, and volcanics of the Gawler Craton. Extensive zones of low-grade mineralisation are known in the Warrior palaeochannel and Wynbring palaeochannel. The Warrior palaeochannel is that part of the Wynbring palaeochannel containing the Warrior uranium deposit (Fig. 31). Further south, mineralisation is known in the Narlaby and Yaninee palaeochannels (Fig. 31).

The Warrior palaeochannel, 55 km west of Tarcoola (Fig. 31), contains variable thicknesses of early Tertiary terrigenous sediments (up to 22 m thick), Eocene fluviolacustrine sediments (up to 66 m) and red–brown–yellow and grey pebbly clays of the Miocene Garford Formation (up to 16 m) (Curtis & others, 1990). Proterozoic granites form the basement. The Warrior deposit occurs within the palaeochannel sediments.

Warrior deposit

PNC Exploration Pty Ltd carried out a major drilling program (514 open holes and 29 cored holes) during 1973–82 that outlined zones of mineralisation in Eocene lignitic strata. Mineralisation is associated with an oxidation interface localised by the present day water table at a depth of approximately 30 m. The strongest mineralisation occurs along the channel margins where the oxidation interface intersects lignitic horizons. The Warrior deposit is a low-grade resource distributed in seven discrete zones along 12 km of the palaeochannel. Drilling outlined an indicated resource of 4000 t U_3O_8 with an average grade of 0.034% U_3O_8 and average thickness of 1.5 m (South Australia Department of Mines & Energy, 1982).

In the **Wynbring** palaeochannel, further west, PNC Exploration reported that uranium occurs in Tertiary sediments overlying Archaean gneiss and granite. The Wynbring channel is 1.4–3 km wide and contains up to 74 m of coarse to fine sand with lignite, mudstone and siltstone interbeds. Significant uranium

Figure 31. Palaeochannels In The Eyre Peninsula Region, South Australia (After Rogers, 1999)

mineralisation coincides with the level of the present water table (less than 20 m below surface) in sand and interbedded lignite (South Australia Department of Mines & Energy, 1983).

From 1979 to 1982 Carpentaria Exploration Company explored Eocene palaeochannel sediments in the northern Eyre Peninsula. The **Narlaby** and **Yaninee** palaeochannels (Fig. 31) were outlined by drilling during this exploration (Binks & Hooper, 1984; Curtis & others, 1990). Proterozoic granitic rocks of the Hiltaba Granite and Lincoln Complex form the basement into which these channels eroded. The Hiltaba Granite has a relatively high uranium content (averaging 7 ppm U) and is believed to be the source of the mineralisation. The Narlaby palaeochannel is about 170 km long and up to 10 km wide and hosts the Yarranna deposit. The Yaninee palaeochannel sediments contain minor uranium mineralisation, but no deposits are known (Binks & Hooper, 1984; South Australia Department of Mines & Energy1984).

Yarranna deposit

At the Yarranna deposit, in the western part of the Narlaby palaeochannel, low-grade uranium mineralisation is associated with redox fronts. The mineralised strata are fine-grained sand and gravel with interbedded clay. In the reduced state the sand is grey to black with variable humic staining, carbonaceous material and minor pyrite; in the oxidised state it is pink to pale brown. The Eocene section is up to 80 m thick and is overlain by up to 100 m of younger sediment. Average grades are in the range 100–200 ppm eU_3O_8 and the mineralisation extends over more than 3 km^2, but the mineralisation is uneconomic (Binks & Hooper, 1984).

WESTMORELAND–PANDANUS CREEK URANIUM FIELD

The Westmoreland deposits are in north-west Queensland, 400 km north-north-west of Mount Isa, in an area contiguous with the Pandanus Creek area in the Northern Territory (Fig. 32).

Pandanus Creek area

A prospector, R.T. Norris, discovered uranium at Pandanus Creek in 1955. The next year, his niece, Eva Clarke, discovered the main deposit at Pandanus Creek — later named the Eva deposit (Lord, 1955; Morgan, 1965). The Cobar 2 deposit, found by A.R. Blackwell in 1956, is 20 km north-north-east of the Pandanus Creek deposit. El Hussen, 5 km south-west of Cobar 2, is another uranium prospect discovered in the mid-fifties. Exploration by Kratos Uranium NL, during 1976–82, located uranium mineralisation along the North-east Westmoreland dyke zone in the Northern Territory.

Westmoreland area

BMR carried out a low-level airborne radiometric survey of the area from September to November 1956 (Livingstone, 1957; Walpole, 1957). A joint venture between Mount Isa Mines Ltd (MIM) and Conzinc Riotinto of Australia Ltd (CRA), which held a Prospecting Authority over the area being surveyed, investigated the anomalies and discovered uranium mineralisation in outcrops of the Westmoreland Conglomerate at the Redtree prospect in November 1956. The joint venturers pegged three leases and later did some drilling (Fuchs & Schindlmayr, 1981). These leases (Redtree Nos. 1, 2 and 3) were held by the joint venturers through to 1997.

The next exploration phase was 1967–75 when Queensland Mines Ltd undertook a major exploration and drilling program for stratabound deposits in the Westmoreland Conglomerate. The company delineated the Jack, Garee and Langi lenses of the Redtree deposit (Fig. 33). The emphasis of exploration shifted to

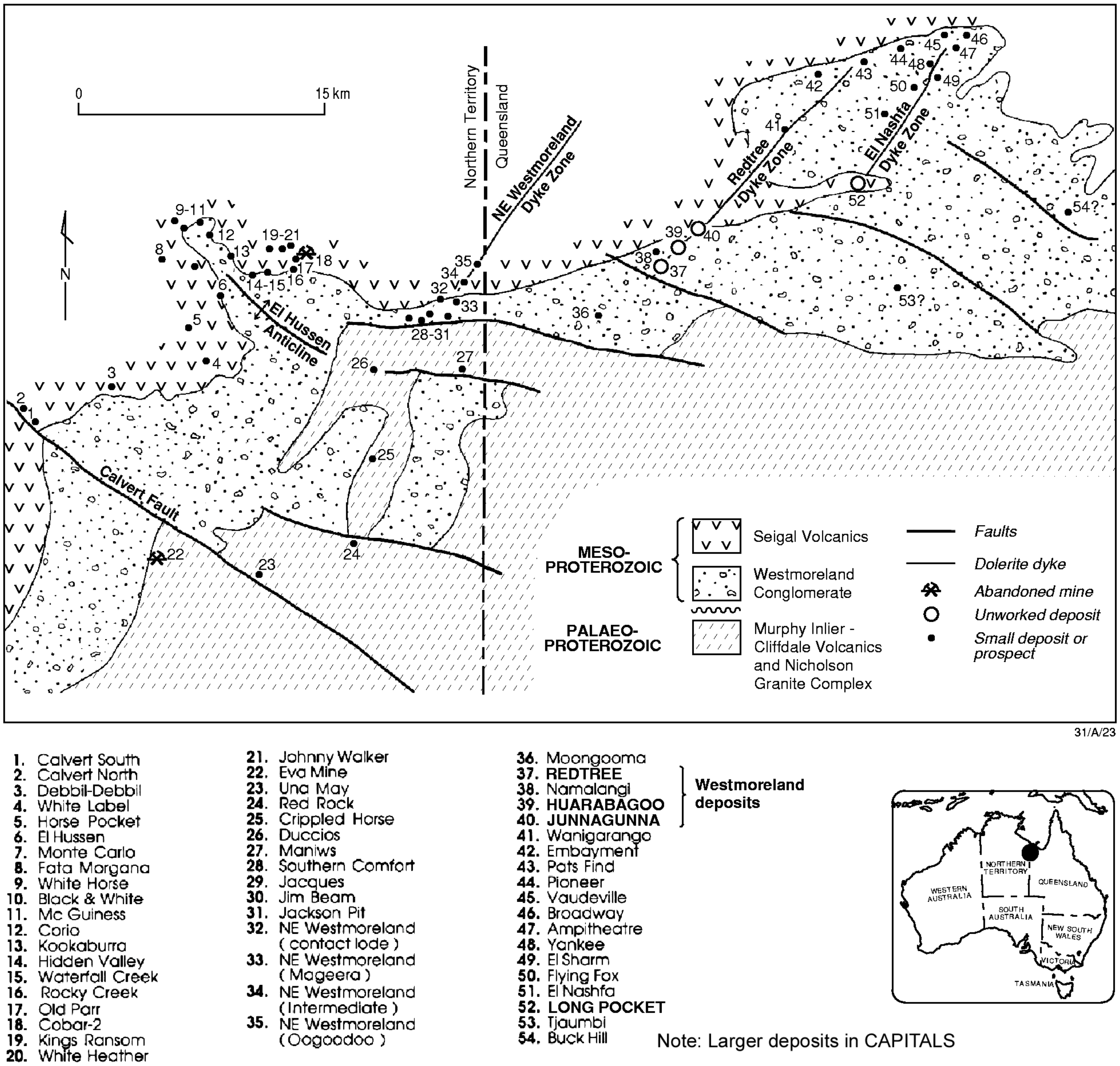

Figure 32. Geological setting of uranium deposits and prospects in the Westmoreland–Pandanus Creek uranium field (after Ahmad & Wygralak, 1989)

north-east-trending structures when high-grade uranium mineralisation was located along the Redtree joint zone to the east of Redtree No. 1 lease. However, the high-grade mineralisation was later found to be discontinuous, and earlier resource estimates were substantially reduced (Fuchs & Schindlmayr, 1981). Exploration continued in the Westmoreland area from 1976 to 1982. A joint venture operated by Urangesellschaft Australia Pty Ltd located the Junnagunna and Sue deposits and delineated the Outcamp deposit.

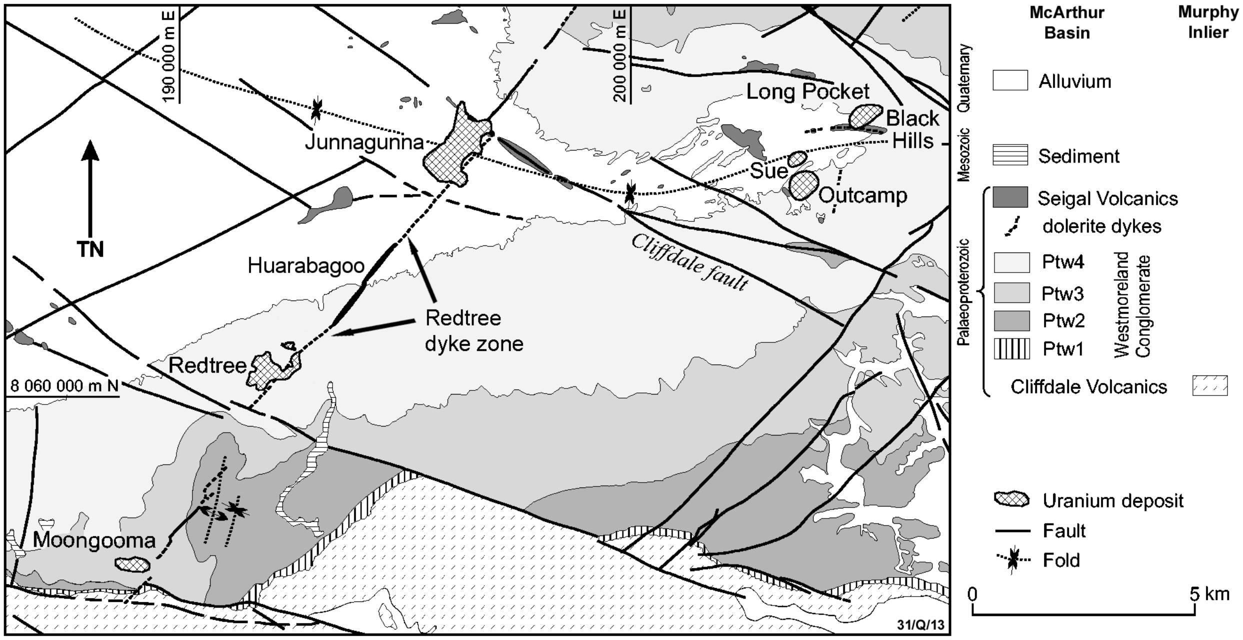

Figure 33. Geology of the Westmoreland uranium deposits (after Rheinberger, Hallenstein & Stegman, 1998)

In 1990, CRA Ltd (now Rio Tinto Ltd) commenced a new phase of exploration at Westmoreland and increased its equity in the joint venture. The company carried out regional exploration and additional infill drilling at Junnagunna and Huarabagoo to delineate the resources (Rheinberger, Hallenstein & Stegman, 1998). The company investigated the feasibility of mining the ore, placing the crushed ore on surface leach pads, and recovering the uranium by heap-leaching methods. Large diameter holes were drilled into the Redtree ore zone to collect bulk samples for leaching testwork, which was carried out by the Australian Nuclear Science and Technology Organisation and Australian Mineral Development Laboratories (AMDEL). Detailed metallurgical testing of ore from Redtree, Huarabagoo and Junnagunna showed that the mineralisation was readily amenable to acid leaching and high recoveries of uranium were achieved (Rheinberger & others, 1998). CRA Ltd acquired full ownership of the Westmoreland deposits in 1997. In 1998 the company completed the drilling program and carried out a re-assessment of the ore resources. From the results of this re-assessment and preliminary feasibility studies, the company decided to withdraw from the project. During 1999 the disturbed areas were rehabilitated and the company applied to relinquish its ownership of the leases and exploration tenements in the Westmoreland area.

The three main deposits — Redtree, Junnagunna and Huarabagoo — have been tested by 699 percussion and reverse circulation holes. In addition, approximately 857 holes have been drilled to test other uranium prospects within the region, mostly in the Westmoreland Conglomerate (Rheinberger & others, 1998).

Regional geological setting

The field is near the south-eastern margin of the Palaeoproterozoic–Mesoproterozoic McArthur Basin (Fig. 32), where it laps to the south onto Palaeoproterozoic basement rocks of the Murphy Inlier. The Murphy Inlier consists of the Murphy Metamorphics, Cliffdale Volcanics and Nicholson Granite Complex (Ahmad & Wygralak, 1989, 1990; Ahmad, 1998). The oldest rocks in the Inlier are Palaeoproterozoic quartz–feldspar–mica schists and gneisses of the Murphy Metamorphics, which are only exposed in the Northern Territory portion.

Palaeoproterozoic acid lavas and ignimbrites (Cliffdale Volcanics) unconformably overlie the metamorphics. The upper units of the Cliffdale Volcanics and the Nicholson Granite have been dated at 1840 Ma (M. Ahmad, Northern Territory Geological Survey, personal communication). Multiphase intrusions of the Nicholson Granite Complex (granites and adamellites) intrude the metamorphics and Cliffdale Volcanics (Grimes & Sweet, 1979; Plumb, Derrick & Wilson, 1980; Sweet, Mock & Mitchell, 1981).

The Murphy Inlier trends east-north-east and its northern flank is unconformably overlain by gently tilted sedimentary and volcanic rocks of the Palaeoproterozoic Tawallah Group (McArthur Basin). The basal unit, the Westmoreland Conglomerate, is a fluvial deposit, more than 1200 m thick, and comprises arkose, conglomerate and quartz arenites. The Westmoreland conglomerate was subdivided into four stratigraphic units (Ahmad & Wygralak, 1989). Most of the uranium mineralisation is within the upper unit (Ptw4 unit), which is porous, coarse-grained sandstone, conglomeratic in part, and 80–90 m thick.

Basaltic lavas of the Seigal Volcanics conformably overlie the Westmoreland Conglomerate, and these are followed by dolomite, sandstone and basic and acid volcanics of the upper part of the Tawallah Group.

Dolerite dykes intrude along north-east trending fault and fracture zones which intersect the Westmoreland conglomerate. The most significant of these are the Redtree and the North-east Westmoreland dyke zones. The Redtree dyke zone is over 15 km long and has been intruded by a complex series of dykes, with individual dykes generally less than 20 m thick (Rheinberger & others, 1998). The Westmoreland uranium deposits (Redtree, Junnagunna and Huarabagoo) are along the Redtree dyke zone. Eight samples from the Namalangi lens of the Redtree deposit gave U–Pb ages for uranium mineralisation of 812 ± 55 Ma (Pidgeon, 1985).

A number of small deposits and prospects occur along the North-east Westmoreland and El Nashfa dyke zones.

According to Schindlmayr and Beerbaum (1986), the origin of the uranium in the Westmoreland deposits is still open to interpretation. Introduction of uranium into the sedimentary system may have taken place either detritally, or by exhalative volcanogenic activity, or by hydrothermal remobilisation from deep-seated sources. These authors also postulate that heatflow at about 820 Ma generated and maintained hydrothermal convection cells in the permeable host rocks. Uranium introduced to circulating oxygenated formation waters by one or more of the above processes was precipitated against physico-chemical barriers such as basic dykes or lavas, due to the abundant supply of divalent iron as a reducing agent.

Hochman and Ypma (1984) made thermoluminescence measurements on some 800 samples from the Westmoreland orebodies and surrounding host rocks up to 8 km away. They concluded that the Westmoreland Conglomerate has suffered major radiation damage attributable to at least 10 ppm uranium over 10^9 years, and that it had a high inherent uranium content that was remobilised in a convective cell system, possibly triggered by intrusion of dolerite dykes or by heat flow along rejuvenated structures.

Rheinberger and others (1998) also consider that the primary conduits for the uranium-bearing fluids are the major north-east structures such as the Redtree dyke zone. Migration of the uranium-bearing fluids away from the structures was controlled mainly by the porosity of the sediments. Uranium was precipitated adjacent to mafic rocks when oxidising groundwaters were reduced by reaction with Fe^{2+} in solution. Hematite also formed during the reactions. Chloride ions released by uraninite precipitation were used in chlorite formation. This explains the hematite–chlorite alteration. The flat-lying mineralisation at Redtree formed immediately underneath the Seigal Volcanics and subsequent erosion of the basalt and weathering of the mineralisation has changed the primary assemblage. Uraninite has weathered to secondary uranium minerals and chlorite has weathered to a mixture of iron oxides and clay (Rheinberger & others, 1998).

The uranium mineralisation at Pandanus Creek has been dated at 850 Ma, and Morgan and Campi (1986) postulated that it was preceded by widespread faulting of the overlying Palaeoproterozoic rocks.

Because the bulk of the known uranium resource is in sandstone, the deposits are collectively grouped here as of sandstone type, even though many deposits, including Eva (Pandanus Creek), Cobar 2 and El Hussen, are in volcanics and belong to the vein type. (Even Westmoreland deposits hosted entirely within the sandstone are regarded as vein-type by some authors.)

Deposits

The uranium deposits and occurrences in the Westmoreland–Pandanus Creek field occur in four main geological settings (Ahmad & Wygralak, 1990), described here as Types 1–4. Although most of the known uranium resources are in the Westmoreland area, all production in this field has come from the small Pandanus Creek and Cobar 2 deposits.

Type 1 consists of stratabound mineralisation in the uppermost sandstone unit (unit Ptw4 in Fig. 33) of the Westmoreland Conglomerate, subparallel to the contact with:

- overlying basic volcanics of the Seigal Volcanics, e.g. Junnagunna, Redtree (Jack, Garee and Langi lenses); this deposit type contains the bulk of the known resources;
- overlying Cliffdale Volcanics, e.g. Southern Comfort; or
- parallel to the contact with intermediate sills, e.g. Long Pocket area.

The Seigal Volcanics normally overlie the Westmoreland Conglomerate, but in places reverse faulting has resulted in Cliffdale Volcanics overlying the conglomerate.

Type 2 consists of discordant, steeply dipping zones of mineralisation adjacent to the contact with basic dykes, e.g. Huarabagoo, Mageera, Oogoodoo and Wanigarango. Stratabound mineralisation may grade into steeply dipping zones of mineralisation, e.g. along the Redtree dyke zone.

Type 3 consists of mineralisation associated with fractures in altered basic volcanics (Seigal Volcanics), e.g. Cobar 2, Old Parr, El Hussen and Kings Ransom.

Type 4 consists of mineralisation associated with shear zones within altered acid volcanics (Cliffdale Volcanics), e.g. Eva mine (Pandanus Creek deposit).

The Broken Hill Proprietary Co. Ltd delineated the **Eva** deposit **(Pandanus Creek** deposit**)** in 1958–59 and South Alligator Uranium NL mined it from 1960 to 1962. Drilling indicated 55 000 t ore averaging 0.56% U_3O_8 to a depth of 42 m. Selective mining to a depth of 25 m produced 312 t high-grade ore averaging 8.37% U_3O_8, which was trucked 1850 km to the treatment plant at Rum Jungle. A spoil dump near the mine contains about 3000 t of material averaging over 1% U_3O_8 (Morgan, 1965; Morgan & Campi, 1986). The deposits occur in en-echelon shear zones up to 2 m wide that strike north-north-east and dip north-west. The host rocks are bleached, intensely altered acid volcanics (Cliffdale Volcanics) overlain by sandstone of the Westmoreland Conglomerate. The orebody is within the contact aureole of a small granite stock, which crops out only 15 m to the west of the margin of the orebody. The ore shoots plunge to the north-north-east, parallel to the granite contact, but no uranium mineralisation has been found in the granite (Sweet & others, 1981; Morgan & Campi, 1986). The youngest granite intruding the host rocks has been dated at approximately 1773 Ma, whereas the uranium mineralisation is dated at

850 Ma. It is unlikely therefore that the orebody was formed by hydrothermal solutions emanating from the granite. Instead, Morgan and Campi (1986) have proposed a hydrothermal origin from solutions ascending along major faults during tectonism. The bulk of the ore is in a band of sericitic quartzite within porphyritic lava. The main ore minerals are pitchblende, gummite, uranophane and sklodowskite. The ore also contains significant amounts of gold and silver.

The **Cobar 2** deposit (Newton & McGrath, 1958) was tested and worked from 1956 to 1959 by North Australian Uranium Corporation NL and produced 72 t hand-sorted ore grading 10.52% U_3O_8, which was trucked to Rum Jungle. The deposit occurred in a steeply dipping shear in altered basalt of the Seigal Volcanics. The main ore mineral was uraninite (McAndrew & Edwards, 1957a,b), associated with hematite.

Other prospects in the Pandanus Creek area include **Kings Ransom**, **El Hussen**, **Old Parr**, **Mageera** and **Oogoodoo** (Fig. 32). The first three are in shears in the Seigal Volcanics. At El Hussen, uranium also occurs along the sheared contact with the Westmoreland Conglomerate (Sweet & others, 1981). At the Mageera and Oogoodoo prospects, uranium is present along the Westmoreland Conglomerate/Seigal Volcanics contact where this is cut by a north-east-trending fault (Kratos Uranium NL, 1982).

In the Westmoreland area most of the deposits are flat-lying lenses flanking the north-east-trending Redtree joint zone (Fig. 33) (Culpeper & others, 1999). Basic dykes are emplaced along the joint zone, the southern part of which is known as the Namalangi section, and the northern part the Huarabagoo section. Uranium mineralisation occurs either as:

- 'horizontal mineralisation' (Fuchs & Schindlmayr, 1981), either subparallel to the contact of the overlying Seigal Volcanics or parallel to intermediate sills in the uppermost units of the Westmoreland Conglomerate, or
- 'vertical mineralisation' as steeply dipping lenses next to and within the Redtree dyke (Fig. 34).

Horizontal mineralisation may grade into vertical mineralisation near the Redtree joint zone (Hills & Thakur, 1975; Schindlmayr & Beerbaum, 1986). Significant horizontal mineralisation may extend up to 600 m away from the zone.

Redtree deposit (Rheinberger & others, 1998) comprises horizontal mineralisation in the **Jack**, **Garee** and **Langi** lenses and vertical mineralisation in the **Namalangi** lens. The deposit occurs at the south-western end of the Redtree dyke zone (Fig. 33). The horizontal mineralisation is entirely hosted by the Ptw4 sandstone and is associated with a chlorite–minor hematite alteration. The **Jack** and **Langi** lenses on the north-western side of the dyke zone form flat lying zones of mineralisation 0–10 m below surface, 0.5–15 m thick and up to 500 m wide. The mineralisation thickens and steepens near the dyke where it is 30–40 m thick. The **Langi** deposit is some 600 m north-east of the Jack deposit. Grades are fairly uniform and average around 0.1% U_3O_8, with torbernite, metatorbernite and carnotite the main ore minerals. Closer to the Redtree joint zone the deposit grades into discontinuous vertical lenses of primary uranium mineralisation.

The **Garee** lens, on the south-eastern side of the dyke zone, is 5–30 m below surface, and up to 30 m thick where it is adjacent to the dyke zone. Mineralisation is mainly pitchblende, with secondary uranium mineralisation at its eastern end.

The **Namalangi** lens comprises vertical mineralisation in the Redtree dyke zone, mainly in the sandstone between the dykes. The dykes exhibit chlorite–calcite alteration at their margins and the Westmoreland Conglomerate is chloritised near the dykes.

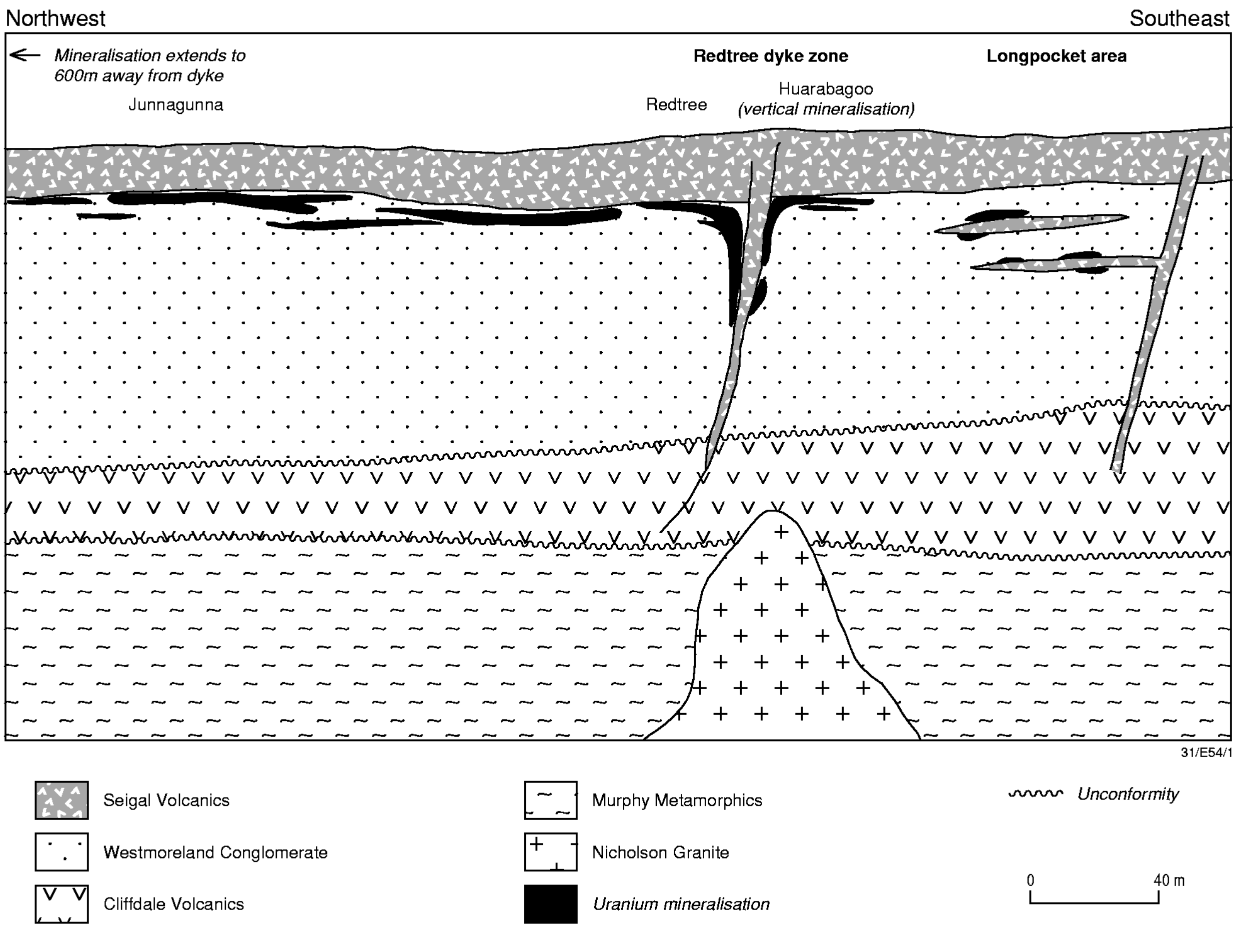

Figure 34. Diagrammatic cross-section of uranium deposits in the Westmoreland area (after Fuchs & Schindlmayr, 1981)

Huarabagoo deposit (Figs 33, 34), 3 km north-east of the Redtree deposit, is a zone of vertical mineralisation in a structurally complex area of the Redtree dyke zone. In this zone there were multiple injections of smaller dykes (steeply dipping and horizontal) associated with the two main vertical dykes. Most of the mineralisation is within the sandstones adjacent to the dykes and the remainder is in the dykes

Junnagunna deposit, approximately 7 km north-east of the Redtree deposit, consists of flat-lying mineralisation within sandstone immediately below the Seigal Volcanics contact. The mineralisation is 20–30 m below surface and 0.5–10 m thick and developed on both sides of the dyke zone, and is associated with chlorite and minor hematite alteration. It is covered by soil and also by the Seigal Volcanics. This deposit was discovered by drilling on radon anomalies.

Long Pocket area contains the **Outcamp**, **Sue** and **Black Hills** deposits (Fig. 33). These deposits are within the Ptw4 sandstone. Mineralisation occurs as a number of horizontal lenses, 0.5–5 m thick, over an area of approximately one square kilometre. Mineralisation occurs along the upper and lower contacts of a subhorizontal dolerite sill approximately 5 m thick (Rheinberger & others, 1998). Approximately 90% of the mineralisation is in sandstones along the contact and the rest is in the sill (Fig. 34).

The **Black Hills** deposit is hosted by Ptw4 sandstone and is adjacent to the contact with the overlying Seigal Volcanics. The mineralisation, which is spatially related to the east-trending Black Hills dyke, appears to be discontinuous and insufficient drilling has been completed at Black Hills to allow an estimate of resources (Rheinberger & others, 1998).

Schindlmayr & Beerbaum (1986) noted that uranium oxides are the main economic minerals at Westmoreland, and secondary uranium minerals of the phosphate, vanadate, silicate, arsenate and sulphate groups are dominant in the weathered parts. In horizontal orebodies open to surface oxidation (Jack, Langi, upper part of Garee) secondary mineralisation is associated with hematite, chlorite and sericite, and forms grain coatings and interstitial fillings. Oxides are the main ore minerals deeper in the Garee deposit, in the horizontal orebodies below volcanics (Junnagunna, Sue, Outcamp), and in almost all vertical-type mineralisation. Uranium and gold mineralisation coexist in places and this association is the youngest mineral phase. Parts of the Junnagunna horizontal-type mineralisation and of the vertical-type mineralisation at Huarabagoo contain gold; values of up to 80 g/t have been obtained, but more commonly the gold assays about 0.2–7.0 g/t.

It was originally thought that the vertical-type mineralisation in the Redtree joint zone had more potential than the horizontal deposits near the joint zone. Later these vertical lenses were found to be discontinuous and the substantial resource tonnages attributed at first to the vertical lenses could not be sustained (Queensland Mines Ltd, 1973; Fuchs & Schindlmayr, 1981). The bulk of the known uranium resource is contained in the stratabound horizontal deposits. Rio Tinto further explored the vertical mineralisation at Huarabagoo in 1990–97 and delineated an inferred resource of 3000 t U_3O_8.

Resources

The resource estimates for the Westmoreland deposits, prepared by Rio Tinto Exploration, are shown in Table 19. Cut-off grade and minimum ore thickness used for these estimates were not reported.

Fuchs and Schindlmayr (1981) estimated the following resources for the Long Pocket area:
Sue deposit, 675 t U_3O_8 in ore grading 0.16% U_3O_8; Outcamp deposit, 945 t U_3O_8 in ore grading 0.16% U_3O_8.

Table 19. Inferred resources, Westmoreland deposits as at 1997 (Rheinberger & others, 1998)

	Inferred resources (Mt)	Grade % U_3O_8	U_3O_8 (t)
Redtree	10.2	0.126	12 600
Junnagunna	5.4	0.098	5 300
Huarabagoo	1.8	0.169	3 000
Total	17.4	0.12	20 900

AMADEUS BASIN

Uranerz Australia Pty Ltd (Uranerz) commenced exploration for sandstone uranium deposits in the Amadeus Basin, Northern Territory, in 1972. Reconnaissance airborne spectrometry and ground surveys in 1972 identified several anomalies south of Alice Springs (Borschoff & Faris, 1990). Drilling of these anomalies during 1973 and 1974 led to the discovery of the Angela and Pamela deposits. From the mid-1970s onwards the project was a joint venture between Uranerz and Carpentaria Exploration Company. Further drilling and mapping showed that the uranium mineralisation occurred along a redox boundary within sandstones of the Undandita Member of the Brewer Conglomerate. From 1975 to 1979 the Angela and Pamela deposits were delineated by detailed percussion and diamond drilling. A number of smaller zones of mineralisation associated with the Angela deposit were also drilled.

The project was placed on care-and-maintenance in 1983, following the introduction of the 'Three mines' policy. In 1990 the joint venture partners requested the NT Department of Mines and Energy to consider placing a Mining Reserve over the area, and that the joint venture be given the first right of refusal to mine the deposit should it become economically viable to do so. In November 1990, a 'Reservation of Land from Occupation' (RO) over the orebody was gazetted by the Department of Mines and Energy. This RO remained in place at the time of writing this report.

Regional geological setting

The regional geology of the intracratonic Amadeus Basin (Fig. 35) has been described by Wells and others (1967, 1970); and Shaw and Wells (1983). A more recent overview of the Amadeus Basin is given by Lindsay and Korsch (1991). The basin sediments range in age from Neoproterozoic to Carboniferous.

The uranium deposits are within the Undandita Member (sandstone) of the Brewer Conglomerate which is the youngest unit in the Amadeus Basin. The Undandita Member is the uppermost unit of the Pertnjara Group, a thick sequence of terrigenous sediments of Late Devonian to Early Carboniferous age. The Undandita Member comprises fine to coarse-grained lithic sandstones, and medium to coarse-grained lithic arkose interbedded with thin mudstone units. This sequence interfingers with the Brewer Conglomerate south of the MacDonnell Ranges (Fig. 36) and reaches a maximum thickness of 3000 m in the Missionary Syncline, 15 km south of Alice Springs. The sediments are generally oxidised, but a wedge-shaped zone of reduced sandstone is preserved within the sequence (Fig. 36) (Borschoff & Faris, 1990).

Angela and Pamela deposits

Angela and Pamela deposits, approximately 28 km south of Alice Springs, are in medium to coarse-grained lithic sandstones (Undandita Member) (Fig. 35). These sandstones are in the broad regional east–west trending Missionary Syncline. Calcite is the main cement with minor quartz. The redox boundary defines the extent of the reduced sandstones within the Undandita Member. The uranium deposits are located along the upper redox boundary (Fig. 36). In cross-section, the higher grade mineralisation at Angela occurs along a 30–40 m high step zone on the upper regional redox boundary (Borschoff & Faris, 1990). This step zone is sub-parallel to the axis of the Missionary Syncline and is remarkably persistent down-plunge. It has been the focus of exploration in the area. Irregularities in lithologies occur across this step zone and its position suggests that it may be related to an east-trending fault. The **Angela** deposit comprises several stacked mineralised horizons each made up of one or more roll-front ore zones (Borschoff & Faris, 1990).

The **Pamela** deposit occurs at the end of the reduced sandstone wedge where a number of steps and irregularities along the redox boundary form a sequence of alternating oxidised and reduced sandstone (Fig. 36). Mineralisation is thinner, weaker and less continuous than at Angela (Borschoff & Faris, 1990).

The primary mineralisation is uraninite and pitchblende with minor coffinite occurring as grain coatings and lining voids. The mineralisation is fine grained to amorphous. Secondary uranium minerals are present in the weathered zone and at depth. These include carnotite, autunite, tyuyamunite and metatyuyamunite. The mineralisation contains vanadium with grades approximately half that of the uranium. The mineralisation is generally in radiometric equilibrium except in the near surface weathered zone. The main gangue mineral is fine-grained hematite which occurs as grain coatings. Pyrite and organic material are negligible (Borschoff & Faris, 1990).

Uranium mineralisation was transported by an oxidising uranium-rich groundwater system and deposited along the regional redox boundary. Borschoff and Faris (1990) suggest that groundwater flowed from north to south with reduced lithologies preserved only in the southern parts of the Missionary Syncline.

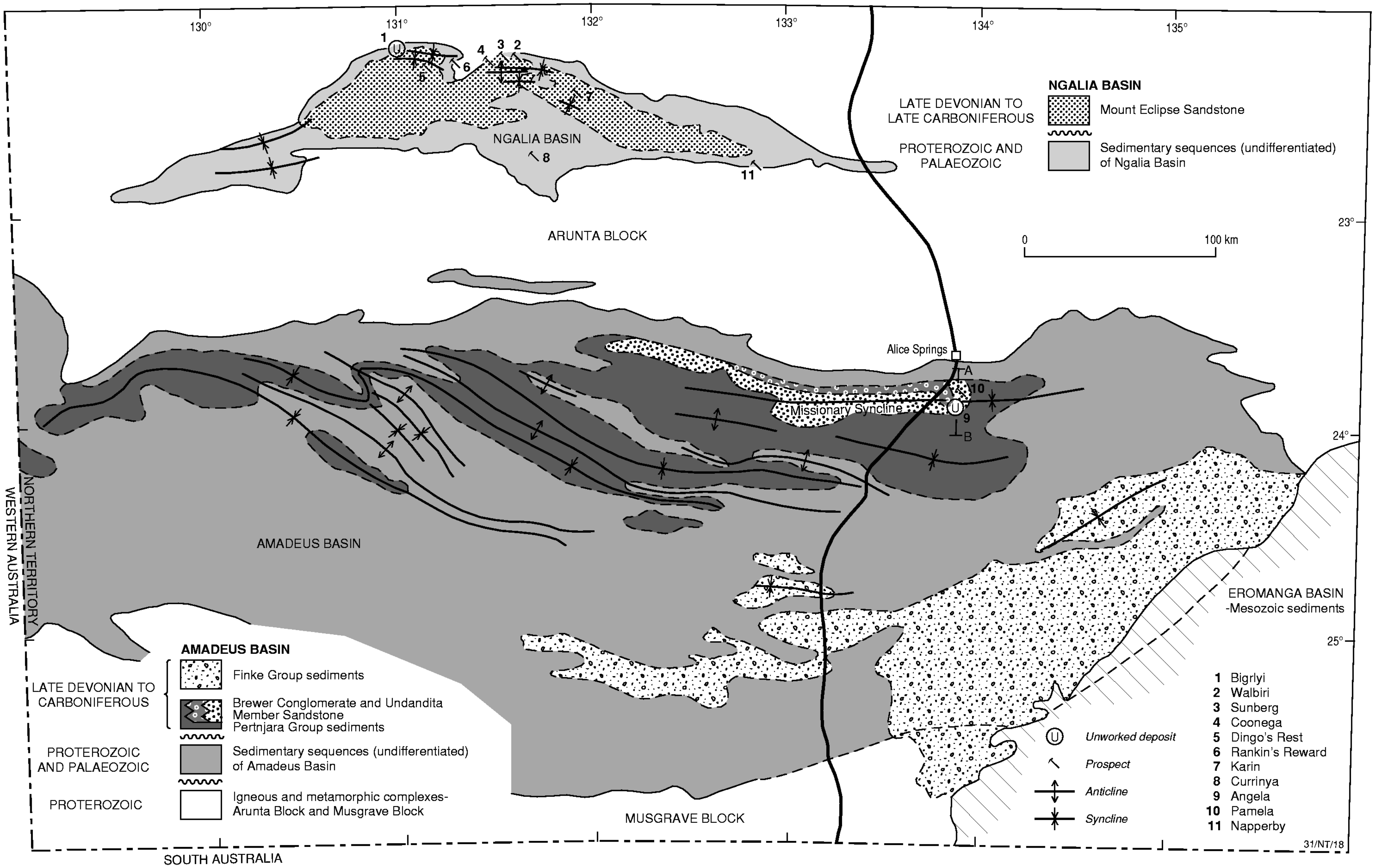

Figure 35. Simplified geology of the Ngalia and Amadeus Basins (NT), showing the Mount Eclipse Sandstone, Pertnjara Group, Finke Group and principal uranium deposits and prospects

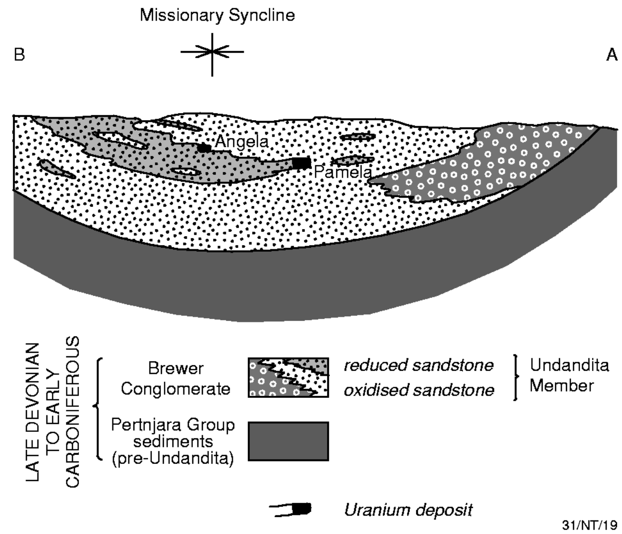

Figure 36. Diagrammatic cross-section of Missionary Syncline showing Angela and Pamela deposits (after Borschoff & Faris, 1990) along line A–B marked on Figure 35

Resources for the Angela deposit have been estimated using a cut-off grade of 0.05% equivalent (e)U_3O_8 and a minimum thickness of 2 m. Above a maximum depth of 650 m there are 4700 t eU_3O_8 measured resources at an average grade of 0.13% eU_3O_8; and an additional 1950 t eU_3O_8 indicated resources averaging 0.1% eU_3O_8 (Borschoff & Faris, 1990). Wider spaced drilling in the deeper western extensions of the Angela deposit and the adjacent northern satellite orebodies showed an inferred resource of 3600–6000 t eU_3O_8 in the grade range 0.1 to 0.13% eU_3O_8. The resources have been calculated using uranium assays derived from down-hole radiometric logging.

NGALIA BASIN

Uranium mineralisation was discovered in the vicinity of the Ngalia Basin (NT) in 1970 when a prospector employed by Central Pacific Minerals NL found radioactive gossanous material in a quartz vein in a granite of the adjacent Arunta Complex to the north of the basin. This prospect was later named Rankins Reward. Further ground prospecting located carnotite in outcrops of the Mount Eclipse Sandstone. The Bigrlyi deposit was discovered in 1973 by ground radiometric traversing and follow-up drilling. Uranium mineralisation was subsequently found in thirteen separate zones in the Mount Eclipse Sandstone (Fig. 35) (Ivanac & Spark, 1976; Fidler, Pope & Ivanac, 1990). In 1973, uranium mineralisation was discovered in Quaternary and Recent calcrete in the southern part of the basin.

Regional geological setting

The Ngalia Basin is an elongate, intracratonic downwarp filled by Neoproterozoic and Palaeozoic strata. The basement rocks are highly deformed metamorphics, granites and sediments of the Palaeoproterozoic Arunta Block (Wygralak & Bajwah, 1998).

Continental and marine strata of Neoproterozoic, Cambrian, Ordovician, Devonian and Carboniferous age comprise the Ngalia Basin sequence. The sequence has been divided into eleven formations with a maximum aggregate thickness of about 7500 m (Wells & Moss, 1983). Most formations are bounded by unconformities. The strata are mainly arenaceous, with interbedded dolomite and shale.

Uranium mineralisation is in the lower part of the Late Devonian to Late Carboniferous Mount Eclipse Sandstone. The host rocks are medium- to coarse-grained feldspathic sandstone with carbonate commonly forming a cement. The sandstones are mainly red, but restricted zones of light to dark grey are also present (Fidler & others, 1990). Minor amounts of shale, siltstone, conglomerate and dolomite are interbedded with the sandstone. The sandstone along the northern margin of the basin is thrust-faulted and folded.

Carnotite is the main ore mineral in the weathered sandstone, with uraninite in the primary zone. Carbonaceous material, including plant remains, is common in the reduced parts of the sandstone.

Quaternary calcrete containing minor carnotite mineralisation has formed in the southern part of the basin where there is a broad area of lagoons, salt-pans and stream meanders related to the present drainage system.

Genesis

Uranium mineralisation in the Ngalia Basin is closely associated with those parts of the Mount Eclipse Sandstone that contain carbonaceous detritus. Prior to diagenesis, run-off from the surrounding highlands permeated the sandstones and migrated into the sediments. In the oxidising environment these waters transported uranium and vanadium which were released from the basement rocks by weathering (Fidler & others, 1990). This uranium and vanadium precipitated in the reducing environment created by the presence of carbonaceous material and pyrite in the sandstones.

Bigrlyi deposit

The Bigrlyi deposit is a series of discontinuous lenses that crop out over a strike length of 12.5 km in the lower part of the Mount Eclipse Sandstone along the northern margin of the Ngalia Basin (Ivanac & Spark, 1976; Wells & Moss, 1983). The host rock is a hard, medium-to-coarse arkosic sandstone, kaolinised in places and containing plant remains and other carbonaceous material. The sandstone sequence is folded, and dips vary from 75°S to 80°N (overturned). Mineralisation consists dominantly of uraninite and montroseite (VO(OH)), which changes to carnotite in the oxidised zones. Vanadium is present in amounts comparable to uranium, although the maximum levels of each element rarely coincide (Fidler & others, 1990). The uranium mineralisation is in radioactive disequilibrium. Gangue minerals are dominantly quartz with very minor orthoclase, kaolin, muscovite, chlorite and calcite.

Detailed drilling has outlined resources in eight separate lenses. Central Pacific Minerals NL (1982) reported 2181 t U_3O_8 proved resources, averaging 0.372%; 486 t U_3O_8 probable resources, averaging 0.252%; and 107 t U_3O_8 possible resources, averaging 0.361%.

Walbiri deposit

The Walbiri deposit comprises several lenses of carnotite mineralisation in white feldspathic sandstone and arkose. The lenses occupy a strike length of 3 km and grade at depth into grey sandstone containing pyrite and carbonaceous matter, including fossil logs. The largest lens of mineralisation is 740 m long, 113 m wide and, on average, 2.1 m thick. It contains 423 500 t ore averaging 0.162% U_3O_8. This represents 686 t U_3O_8 (Central Pacific Minerals NL, 1976).

Other deposits

The **Dingo's Rest** prospect consists of carnotite in coarse arkosic sandstone which dips between 14° and 40°S. The carnotite is closely associated with clay pellets and purple hematite, and also forms fracture fillings, pore fillings, grain coatings and segregations. The deposits may be related to the mottled zone of lateritisation (Wells & Moss, 1983).

The **Sunberg**, **Coonega** and **Karin** prospects also consist of carnotite; at Karin, uraninite also occurs in the primary zone.

GUNBARREL BASIN

The Mulga Rock uranium deposits are 230 km east-north-east of Kalgoorlie (WA) (Fig. 23). In 1978, PNC Exploration (Australia) Pty Ltd (PNC) used widely-spaced reconnaissance drilling to explore for sandstone-type uranium deposits in Permian and Cretaceous arenites in the south-western parts of the Gunbarrel Basin. The Gunbarrel Basin comprises Phanerozoic sediments previously considered to be part of the Officer Basin (Hocking, 1994). The Officer Basin now comprises the underlying deformed Neoproterozoic sediments.

Uranium mineralisation was intersected in 1979. Drilling from 1980 to 1988 delineated three deposits (collectively referred to as the Mulga Rock deposits) hosted by Eocene palaeochannel sediments. Since 1978 a total of 2041 holes have been drilled within an area of 2500 km^2 (Fulwood & Barwick, 1990). The mineralisation does not crop out and in 1983 a 30 m deep open cut was excavated and large samples of higher grade material were collected for metallurgical tests. Trial leaching tests were carried out on-site.

Regional geological setting

The regional geology has been described by Bunting and Boegli (1977), Bunting and van de Graaff (1977) and Jackson and van de Graaff (1981).

The Mulga Rock palaeochannel was eroded into mudstone of the Paterson Formation (Carboniferous–Permian) in the south-western extremity of the Gunbarrel Basin. The Paterson Formation unconformably overlies granitoids and metamorphics of the Archaean Yilgarn Block to the west and Proterozoic Albany–Fraser Province to the east. The palaeochannel as outlined by drilling is known over a distance of at least 100 km beneath the Tertiary cover rocks (Fulwood & Barwick, 1990). The western portion of the channel connects with the present day drainage system of Lake Raeside and Ponton Creek. Continuation of the palaeochannel to the south is within the Queen Victoria Springs Fauna and Flora Reserve.

Within the palaeochannel, up to 140 m of flat-lying sand, silt and gravels disconformably overlie mudstone of the Paterson Formation. These sediments range from Cretaceous to Tertiary in age. In places the mudstone has been removed by erosion and the younger sediments directly overlie metamorphics of the Albany–Fraser Province. The sedimentary sequence within the palaeochannel is summarised as follows (Fulwood & Barwick, 1990):

- at the bottom, *Cretaceous lacustrine sediments* (approximately 60 m thick), with a pebble gravel unit 2–3 m thick at their base, grade upwards into a sequence of quartz sand and sandy clays;
- at the top, *Tertiary fluviatile-lacustrine sediments* (approximately 80 m thick) conformably overlie the Cretaceous sands. The Tertiary sediments consist of a sequence of interbedded clay, peaty clay and peat that is Middle Eocene in age. The uranium mineralisation is hosted by peat layers within this sequence. Conformably overlying this is a sequence of quartz sand, silt and clay up to 30 m thick, which has been completely oxidised.

Quaternary sediments (approximately 20 m thick) consisting of aeolian sand, laterite and silcrete overlie the whole region.

Mulga Rock deposits

The Mulga Rock deposits comprise three separate zones of mineralisation — **Shogun**, **Emperor** and **Ambassador** deposits. These occur along the outer margin of a broad bend in the palaeochannel.

The uranium mineralisation is hosted by peat and clayey peat and occurs immediately below the redox boundary at the base of the weathered zone. The base of the weathered zone is sharply defined and is close to the level of the water table (Butt & others, 1994). The mineralised zones are flat-lying and are from 20 to 50 m below surface, depending on changes in surface elevation and fluctuations in the level of the redox boundary. The mineralised zones average about 2 m thick.

Uranium has been adsorbed onto the organic matter within the peat (Fulwood & Barwick 1990). Uranium minerals are generally not present. However, rare discrete grains of coffinite and uraninite have been identified (Butt & others, 1994).

Genesis

During Tertiary weathering, uranium was leached out of granitoids and metamorphics of the Yilgarn and Albany–Fraser Provinces. Oxidising groundwaters within the sediments transported dissolved uranium (as hexavalent uranyl ion) along the palaeochannel. Uranium was fixed by adsorption when it came into contact with organic material in the peat layers. The peat accumulated in an organic-rich paludal environment during the Eocene.

During the Cainozoic, weathering resulted in oxidation of the surface sediments down to a depth of approximately 30 m; the uranium within these sediments was dissolved by oxidising groundwaters. The mobilised uranium was later re-adsorbed onto peat layers at the base of the oxidised zone. Repeated oxidation, downward movement and re-adsorption of the uranium were also assisted by seasonal fluctuations in the height of the water table. Consequently, low-grade mineralisation, originally deposited in the organic-rich sediments, was later concentrated by supergene processes that resulted in uranium accumulating within peat layers at the base of surface oxidation. This generally corresponds to the level of the water table. The grade of mineralisation and thickness are controlled by permeability and organic-matter-content of the host sediments — the highest grades and thickest zones of mineralisation are developed within the more organic-rich and more permeable sediments.

The Mulga Rock mineralisation is in a state of radiometric disequilibrium that varies with depth below the surface. Oxidised sands and silts above the redox boundary are depleted in uranium compared to daughter products. In contrast, reduced sediments immediately below the redox boundary are enriched in uranium relative to daughter products (Fulwood & Barwick, 1990).

The total resources within the Emperor, Shogun and Ambassador deposits were estimated to be 10.8 Mt averaging 0.12% U, which corresponds to 13 000 t U (15 330 t U_3O_8). The resource was calculated using a cut-off grade of 0.03% U and a minimum grade x thickness factor of 0.1 m% U (Fulwood & Barwick, 1990). The resources are 2 m thick, on average.

CARNARVON BASIN

Minatome Australia Pty Ltd explored Proterozoic rocks of the Gascoyne Block, WA (Fig. 23) from 1972 to 1975 and established that the Proterozoic granites in the area are enriched in leachable uranium. Water bores were sampled and analysed and it was established that groundwater from Cretaceous and Cainozoic strata of the Peedamullah Shelf of the Carnarvon Basin contains significant amounts of uranium.

Attention was focused on Cretaceous conglomerate and sandstone (Valsardieu, Harrop & Morabito, 1981). During 1973 and 1974, Minatome carried out airborne radiometric surveys over Cretaceous rocks along the eastern edge of the Peedamullah Shelf, but no significant radiometric anomalies were recorded. The company then decided to explore for palaeochannels in the basement, which were delineated by an interpretation of the regional magnetic intensity maps published by BMR. Widely spaced rotary-mud drilling was started in 1974 using down-hole logging (gamma ray, resistivity, SP). Several palaeochannels were confirmed. The Cretaceous strata encountered were oxidised in places by circulating groundwater. Anomalous radioactivity was recorded in four holes near Crow Plain Well, and this led to the discovery of the Manyingee uranium deposit (Valsardieu & others, 1981). Urangesellschaft Australia Pty Ltd and Aquitaine Australia Minerals Pty Ltd later formed a joint venture with Minatome to complete the detailed drilling and evaluation.

During the early 1980s, Total Mining Australia Pty Ltd acquired Minatome's and Aquitaine's equity in the project. Pumping tests carried out on the mineralised sands showed that the aquifer is permeable and is suitable for in situ leaching. Total Mining decided to test the latest methods of in situ leach mining, which had been developed at mining operations in Wyoming. Approval to carry out these tests was granted after a comprehensive Notice of Intent (similar to an environmental impact statement) was submitted to the Western Australian Department of Mines.

A five-spot in situ leach trial was carried out in 1985 for five months. This comprised four injection wells, a central pumping well and several monitoring wells. Oxygen, hydrogen peroxide and sodium hypochlorite were used as oxidising agents, and carbon dioxide was used as an alkaline leach. Approximately 470 kg of uranium concentrates were produced during the trials. The results of the trials were considered to be disappointing because of the variations in permeability at the test location (Bautin & Hallenstein, 1997).

Paladin Resources Ltd acquired the project in 1998 and started exploration work to further test the Manyingee deposit.

Regional geological setting

The regional geology is described in the Explanatory Notes on the Yarraloola, Wyloo and Yanrey 1:250 000 geological sheets (Williams, 1968; van de Graaff & others, 1977). Knowledge of the sub-surface geology and stratigraphy of the Peedamullah Shelf is based on data from oil exploration drill holes (Condon, 1965; Thomas & Smith, 1976).

The basement rocks are Archaean (?) to Mesoproterozoic metasediments and granite. There is a major unconformity between the basement rocks and the Carnarvon Basin shelf strata. Basal terrestrial conglomerate in palaeochannels is succeeded by other formations that transgress basement to the east. The Cretaceous, shallow-water-marine Birdrong Sandstone overlies the conglomerate and in turn is overlain by marine shale and radiolarite. The uranium is in sandstone units in the palaeochannels. Cainozoic calcareous siltstone, clay and gravel overlie the Cretaceous strata with an erosional hiatus.

Manyingee deposit

The Manyingee deposit (Fig. 37) is 75 km south of Onslow. The palaeochannel found during the initial exploration phase was more precisely delineated by gravity surveys and closely spaced drilling. Where the mineralisation occurs, the base of the channel is 160–180 m below the surface and the channel is 2–3 km wide (Valsardieu & others, 1981). Proterozoic granite forms the basement. The Cretaceous units in the palaeochannel are (from top to bottom):

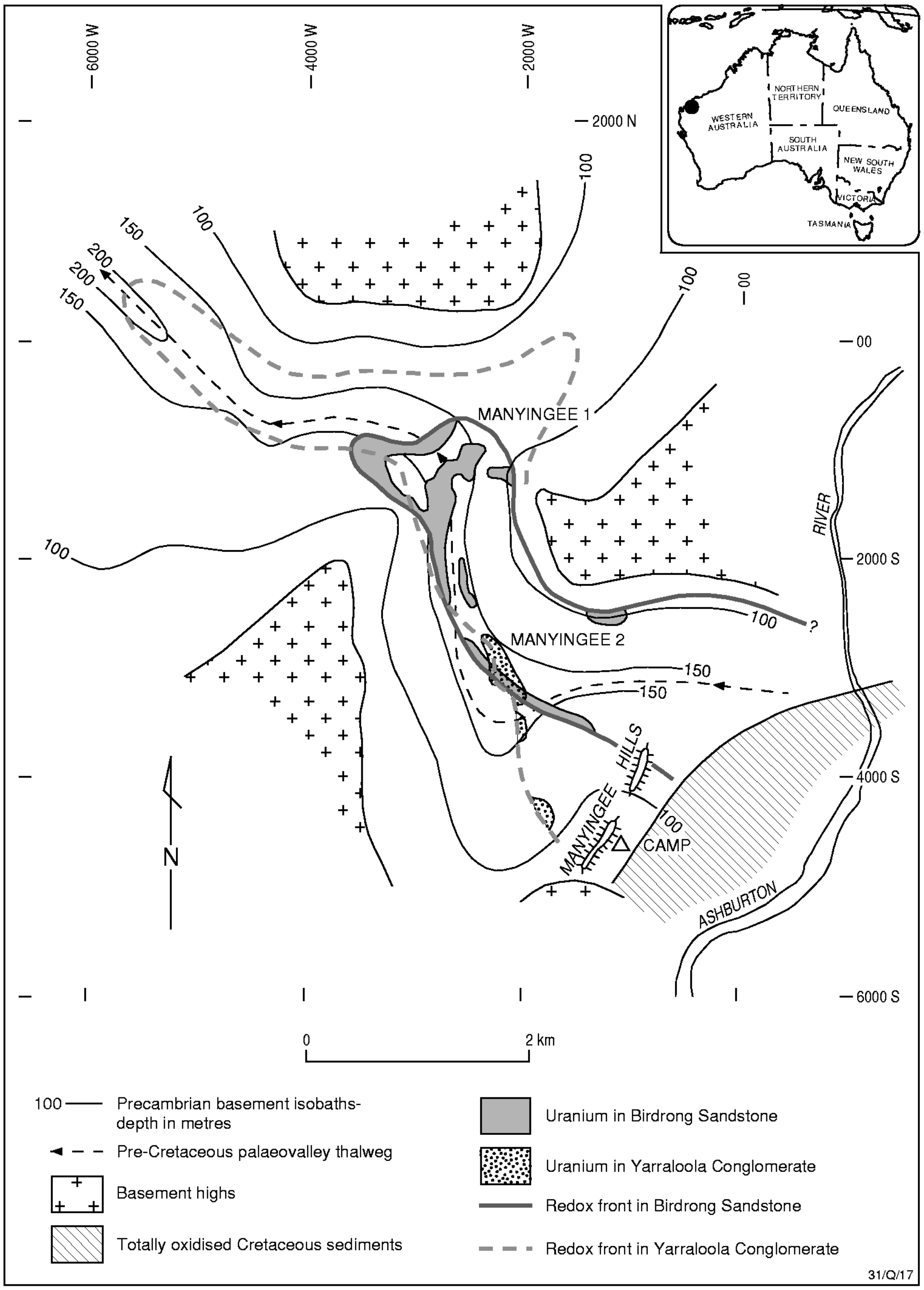

Figure 37. Geological plan of Manyingee deposit (after Bautin & Hallenstein, 1997)

- Windalia Radiolarite, which averages 2 m thick and conformably overlies the Muderong Shale;
- Muderong Shale, which is a fine-grained glauconitic shale conformably overlying Birdrong Sandstone;
- Birdrong Sandstone, which conformably overlies the Yarraloola Conglomerate.
- Yarraloola Conglomerate which is discontinuous, occurs only in the palaeochannel, averages about 60 m thickness, rests unconformably/disconformably on granite and arkose, is polymictic and has well rounded clasts.

The Birdrong Sandstone is less than 50 m thick and the main rock types in the mineralised areas are:

- poorly sorted coarse and medium-grained feldspathic sandstone; clasts include lithic fragments, muscovite, wood and lignite;
- well sorted quartz sandstone, rich in pyrite;
- greenish siltstone and claystone.

Uranium mineralisation is in the lower part of the Birdrong Sandstone and the Yarraloola Conglomerate, and is associated with intense oxidation of the originally reduced sediments by groundwaters moving along the confined aquifer below the Muderong Shale. The groundwater contained soluble uranium that was precipitated in the transition zone between oxidised and reduced sediments to form layers and roll-front deposits.

The permeability of the individual rock units and the morphology of the palaeochannel controlled the migration of groundwater and the deposition of uranium. The main minerals within the layers and roll-fronts are uraninite and coffinite. Minor amounts of phosphuranylite, meta-autunite, siderite and limonite are also present.

Potentially economic uranium mineralisation occurs in two connected lenses referred to as Manyingee 1 and Manyingee 2 (Fig. 37). Manyingee 1 is within the lower Birdrong Sandstone and the upper Yarraloola Conglomerate, at depths ranging from 70 m to 100 m. Manyingee 2 occurs close to the lower Birdrong Sandstone–Yarraloola Conglomerate contact, at depths ranging from 45 m to 95 m (Bautin & Hallenstein, 1997).

Total mineral resources are approximately 7000 t U_3O_8. Depending on the constraints applied to estimate the resources recoverable by in situ leach methods, e.g. the minimum grade thickness accumulation, the recoverable resources are 'in the order of 5000 t of uranium oxide' (Bautin & Hallenstein, 1997).

Other deposits

Reconnaissance drilling by both Minatome and CRA Exploration Pty Ltd during the early 1980s identified a number of palaeochannels in basement rocks below Carnarvon Basin sediments to the north and south of Manyingee. Uranium mineralisation similar to Manyingee is known at Bennetts Well, approximately 10 km south of Manyingee, and also in the Spinifex palaeochannel, 15 km north of Manyingee (Valsardieu & others, 1981). The **Bennetts Well** deposit (Fig. 23) was discovered by CRA in the early 1980s during exploration and drilling along the palaeochannel. The deposit consists of two tabular zones of mineralisation along a redox boundary within the Birdrong Sandstone. Total resources were estimated to be 1500 t U_3O_8 averaging 0.16% U_3O_8 (Eagle Bay Resources NL, 1998).

CANNING BASIN

From 1978 to 1983, Afmeco Pty Ltd explored for sandstone-type deposits along the northern edge of the Canning Basin, in the north of Western Australia (Fig. 23). The area was selected partly because the sedimentary strata have been derived from erosion of the Halls Creek–King Leopold Orogen which contains high levels of background uranium and several small uranium occurrences. Interpretation of Landsat imagery and data from petroleum exploration wells were used in conjunction with available regional geological maps to define the broad extent of Palaeozoic and Tertiary sandstone sequences and their stratigraphy. Initial reconnaissance was followed by a major program of detailed exploration and stratigraphic drilling in five main areas (Botten, 1984). Areas of interest were investigated in detail by airborne geophysical surveys (magnetic and radiometric), gravity surveys, hydrogeological studies, detailed drilling and down-hole geophysical surveys.

In 1980, reconnaissance drilling intersected significant mineralisation at the deposit now known as Oobagooma, 75 km north-east of Derby. Following the discovery, a program of drilling was carried out to better define the deposit. To the end of 1983, a total of 57 000 m of reverse-circulation drilling and diamond drilling was completed for regional exploration and for evaluation of the Oobagooma deposit. The maximum depth of drilling was 250–300 m (Botten, 1984). Afmeco considered that the deposit would be amenable to in situ leaching. Pumping tests were carried out and the results confirmed that the host sandstone is sufficiently permeable to allow uranium to be recovered using this method (Bautin & Hallenstein, 1997).

Only a very limited amount of work was carried out on the project after 1983. Paladin Resources Ltd purchased the project from Afmeco in 1998.

The deposit is within the area of the Yampi Military Training Ground. The training area was created in 1978 by the Commonwealth Government's acquisition of three pastoral leases in the Yampi area.

Regional geological setting

The regional geology of the northern part of the Canning Basin has been described by Veevers and Well (1961), Forman and Wales (1981), Towner and Gibson (1983) and Botten (1984).

Evidence from reconnaissance drilling and lithological studies of strata in the northern part of the Canning Basin has indicated that the major erosion of rocks in the Halls Creek–King Leopold Orogen, together with the release of uranium into the basin, took place from the Early Devonian to Early Permian. More than 60% of the detrital material in strata of this age was derived from erosion of the rocks of the Orogen.

The area underwent a major glaciation in the Early Permian, and the glacial strata (Grant Group), deposited over large areas of the Canning Basin, contain only minor amounts of detrital material from the Orogen, thus reducing their uranium potential. Thus, the search was concentrated in strata older than the Grant Group and close to the margin of the basin (Botten, 1984).

Detailed stratigraphic drilling defined five major palaeodrainage systems (named 'embayments') on the Lennard and Billiluna shelves. These palaeochannel systems were active during two major periods of clastic sedimentation:

- a Late Devonian deposition of fanglomerate directly into a rapidly subsiding basin; these conglomerates crop out extensively along the northern margin of the basin; and
- a Late Devonian–Early Carboniferous deposition of fluviatile and deltaic sandstone as more mature drainage systems extended out into the basin; for example, the Yampi, Barramundi, Sparke Range and Knobby sandstones.

Of the five palaeodrainage systems studied, only the Yampi embayment was found to contain potentially economic mineralisation (Botten, 1984). Mineralisation does not occur in the other palaeodrainage systems probably indicating that the depositional environments and redox conditions in those sandstones were unsuitable for uranium precipitation.

Oobagooma deposit

The Oobagooma deposit is hosted by the Early Carboniferous Yampi Sandstone within the Yampi Embayment. The embayment is a fault-controlled graben which trends north-west and is flanked on three sides by Proterozoic metamorphics. The stratigraphic sequence in the embayment is shown in the table below.

Age	Stratigraphic unit	Lithology and thickness
post Permian		sediments; 20 m
Early Permian	Grant Group	sandstone, siltstone; <200 m
Carboniferous	Yampi Sandstone	interbedded sandstone, siltstone; 60–150 m
Late Devonian–Early Carboniferous	Lillybooroora Conglomerate	pebble conglomerate; <50 m

The Yampi Sandstone was deposited in a delta environment influenced by tidal and fluviatile processes (Botten, 1984). Mineralisation is hosted by sandstones containing abundant organic matter and pyrite. Higher-grade mineralisation is in two zones: an upper band 1–5 m thick at 48–55 m depth, and a lower band 1–6 m thick at 65–85 m depth. In the upper band, mineralisation forms a roll-front deposit (Brunt, 1990). Overall the mineralisation appears to be controlled by a combination of sedimentological, structural and redox factors.

Total mineral resources are estimated to be 10 000 t U_3O_8 at an average grade of 0.12% U_3O_8. Depending on the cut-off grade and the minimum grade x thickness accumulation used for in situ leach calculations, the recoverable resources are between 3000 and 7000 t U_3O_8 (Bautin & Hallenstein, 1997).

OTHER PROSPECTS

In the northern part of the **Drummond Basin** in central eastern Queensland, several irregular zones of low-grade mineralisation occur in the Early Carboniferous Bulliwallah Formation, approximately 80 km south-south-east of Charters Towers (Noon, 1979). The geology of the northern part of the Drummond Basin has been described by Olgers (1972) and Wyatt and Jell (1980). Getty Oil Development Company Ltd, in conjunction with North Queensland Mining Pty Ltd, drilled the area extensively in the mid 1970s. Host rocks are feldspathic quartz sandstone with interbedded mudstone. In places they have a high phosphate content.

Mesozoic sandstones in the **Carpentaria Basin** and **north-western Eromanga Basin** overlie the eastern and southern margins of the Mount Isa Block. They were derived from Mesoproterozoic metasediments and granite. PNC Exploration Pty Ltd tested the sandstone in the **Boulia Shelf** south of Mount Isa (McKay, 1982; Dunn, 1983), and found that the thin Mesozoic and Cainozoic strata overlie both the Proterozoic metasediments of the Mount Isa Block and the Cambrian–Ordovician sedimentary rocks of the Georgina Basin. Reconnaissance percussion drilling defined the Mesozoic Binfield palaeochannel in the Burke River area, 75 km north of Boulia. It contains fluvial sandstone and carbonaceous pelite of the Longsight Sandstone and Wilgunya Formation (Cretaceous). A redox boundary was outlined, but only very low-grade mineralisation was intersected. In the Carpentaria Basin, the Eulo Queen Group (Jurassic) and Gilbert River Formation (Early Cretaceous) were considered favourable hosts (Brunt, 1972), so they were also tested. Sandstone of the Gilbert River Formation was drilled in areas where it overlies the eastern edge of the Mount Isa Block. Low-grade mineralisation was intersected in sandstone (containing carbonaceous matter and pyrite) in the Glen Isla and Malakoff areas, 15 km east of Quamby (Mines Administration Pty Ltd, 1980) (see Fig. 39 in the next chapter).

In the **Gilberton Basin** there are zones of low-grade mineralisation in reduced sandstone of the Gilberton Formation (Late Devonian), 350 km west of Townsville (Qld).

Uranium mineralisation was intersected by Uranerz Australia Pty Ltd in Mesozoic and Cainozoic lignitic sands and sandstone in palaeodrainage channels eroded into Proterozoic rocks along the western margin of the **Bangemall Basin** (WA) (Carter, 1981).

In the **Bonaparte Basin**, secondary uranium mineralisation occurs at the **Horse** prospects in sandstone of the Devonian Galloping Creek Formation, about 260 km north-north-east of Halls Creek (Hassan, 2000).

SURFICIAL DEPOSITS

In Australia, surficial deposits are found only in calcrete. The main uranium-bearing calcrete deposits are in Western Australia in the Yilgarn Craton, at Yeelirrie, Lake Way, Lake Maitland and Centipede, but there are some others, both within and outside the Yilgarn Craton. There are minor uranium-bearing calcrete deposits in other States.

CALCRETE DEPOSITS OF THE YILGARN CRATON

Secondary uranium–vanadium mineralisation was found in 1953 in surficial deposits at Lake Dundas, a few kilometres south of Norseman. Carnotite in calcrete was located about 20 km south-east of Mundong Well in 1961 when airborne radiometric anomalies delineated by a BMR survey (Gardener & Jones, 1967) were checked by ground investigation. It was not until the late 1960s that uranium exploration was directed towards sediments within the Tertiary drainage channels and playa lakes overlying the Yilgarn Craton (Carter, 1981).

In 1969, Western Mining Corporation Ltd (WMC) commenced an exploration program to investigate the potential of the valley-fill sediments to host sandstone-type uranium deposits (Duncan & Levy, 1981; Cameron, 1991a). Small amounts of mineralisation were discovered in calcretes near Nowthanna Hill. In early 1970, BMR released the results of its regional reconnaissance aerial magnetic and radiometric survey over the Sandstone 1:250 000 map sheet. A large radiometric anomaly was detected over the drainage system flowing eastwards into Lake Miranda (Gerdes & others, 1970). The area was pegged in June 1970 by WMC and the anomaly was investigated by detailed ground radiometrics during which the field crew located the only outcrop of ore-grade mineralisation (Cameron, 1991a). However, the first auger holes into the Yeelirrie deposit were not drilled until 1971 (Cameron, 1990). In January 1972, WMC announced the discovery of the Yeelirrie deposit. Following this announcement, intensive exploration activity over the Yilgarn Block and adjacent areas resulted in the discovery of over 62 calcrete uranium occurrences (Butt, Horwitz & Mann, 1977) with resources being delineated at Lake Way, Centipede, Thatcher Soak, Lake Mason, Lake Raeside and Lake Maitland.

Regional geological setting

The term 'calcrete' is applied to accumulations (chemical precipitates) of calcium and magnesium carbonates in surficial sediments within Tertiary drainage systems. Calcretes have been forming under arid to semi-arid climatic conditions since the Pliocene. Carnotite mineralisation is widespread in calcreted trunk valleys of the Tertiary drainage system that developed over 400 000 km^2 of south-western Australia (Gaskin & others, 1981). However, the known calcrete-hosted uranium deposits and significant prospects are confined to the granitic rocks in the northern part of the Yilgarn Craton (Fig. 23). Anomalous concentrations of surficial uranium mineralisation in calcreted drainage channels extend north of the Yilgarn Craton and are found in the Proterozoic Gascoyne Complex and Bangemall Basin and the Archaean Pilbara Craton, as well as in parts of South Australia and Northern Territory (Butt, Mann & Horwitz, 1984).

The distribution of significant calcrete uranium deposits is controlled by the extent of the Yilgarn Craton, the 'Meckering line' to the west and the 'Menzies line' to the south (Butt & others, 1977). The Meckering line marks the eastern limit of erosion by rivers flowing to the west and south. This erosion resulted from uplift of the western part of the continent. The Menzies line, at about 29–30°S, reflects differences in climate, soil-type and vegetation to the north and south of the line.

Calcrete accumulations may be up to 100 km long and 5 km wide and are aquifers. The 'valley' calcretes are located in an arid area characterised by infrequent heavy rains of late summer cyclones (Arnold, 1963). According to Gaskin and others (1981), valley calcretes indicate an environment functioning as a giant concentrating system in which components are leached from the weathered rock of a large catchment area and the products are deposited in a relatively small well-defined area. The northern Yilgarn catchments cover extensive areas of Archaean granitic rocks containing 2–25 ppm U. Oxidising conditions have prevailed in places to depths of 300 m, and uranium has been mobilised as uranyl ion complexes and transported laterally in groundwater. Where these groundwaters reach valley axes the water table rises to within 5 m of the surface. There, evaporation and loss of carbon dioxide promotes precipitation, particularly of carbonates of calcium and magnesium. Conditions governing carnotite deposition are complex, but Gaskin and others (1981) stated that where the solubility product of the concentration of active ion species of uranium, vanadium and potassium exceeds the solubility product of carnotite, this mineral is precipitated in fissures or between carbonate and clay particles.

Butt and others (1984) classified the main uranium deposits into three main types according to their geomorphological characteristics:

- *valley deposits* in calcrete and associated underlying sediment in the central channels of major drainage systems and in the platforms and chemical deltas where these drainages enter playas (e.g. Yeelirrie, Lake Way, Centipede and Lake Raeside);
- *playa deposits* in near-surface evaporitic and alluvial sediments of playas, which, north of latitude 29°S, also contain calcrete (e.g. Lake Maitland, Lake Austin);
- *terrace deposits* (e.g. Minindi Creek), west of the Meckering line, mainly in the Narryer Complex and Gascoyne Complex. In upper terraces near the drainage divide of the Gascoyne River, minor concentrations of uranium are present. In lower terraces, moderately high grades occur in calcrete and underlying sediment, but most occurrences are too small to be economic.

Yeelirrie deposit

The **Yeelirrie** deposit, 650 km north-east of Perth, is within valley calcretes lying along the drainage channel of a broad flat valley located in the northern part of the Yilgarn Craton (Fig. 23). The Yeelirrie catchment area is developed almost entirely on highly weathered granitic rocks (Fig. 38). Along the extreme western margins the drainage has encroached onto mafic volcanics and intrusives of the Montague Range greenstone belt (Cameron, 1990).

The present day ephemeral drainage is generally regarded as the remains of an extensive Early Cretaceous river system that drained the Yilgarn Craton. Rejuvenation in the Tertiary etched this mature pattern into the lateritised peneplain (Cameron, 1991b). Calcrete is developed at the top of the alluvial sediments filling the palaeochannel, and represents a late-stage modification of the alluvial valley-fill sediments. As yet, the precise age of the calcrete is unresolved, but it is probable that calcrete formation extended over a considerable period in recent geological time, even to the present when some varieties are still being formed (Cameron, 1991b).

In the general area of uranium mineralisation, the valley-fill sediments comprise three main lithological units (Cameron, 1984): overburden, calcrete and a clay–quartz unit (combined thickness about 30 m). The *overburden* (1–2 m thick) of sandy, friable grey–brown soil is locally indurated by silica and passes down into carbonated loam.

Two types of calcrete are present within the *calcrete layer* — one is a pale brown, friable, ‘earthy’ type and the other is a white, hard, nodular, ‘porcellanous’ type, which is commonly riddled with voids. The earthy calcrete forms a fairly continuous layer that grades upwards into the overlying soils. The

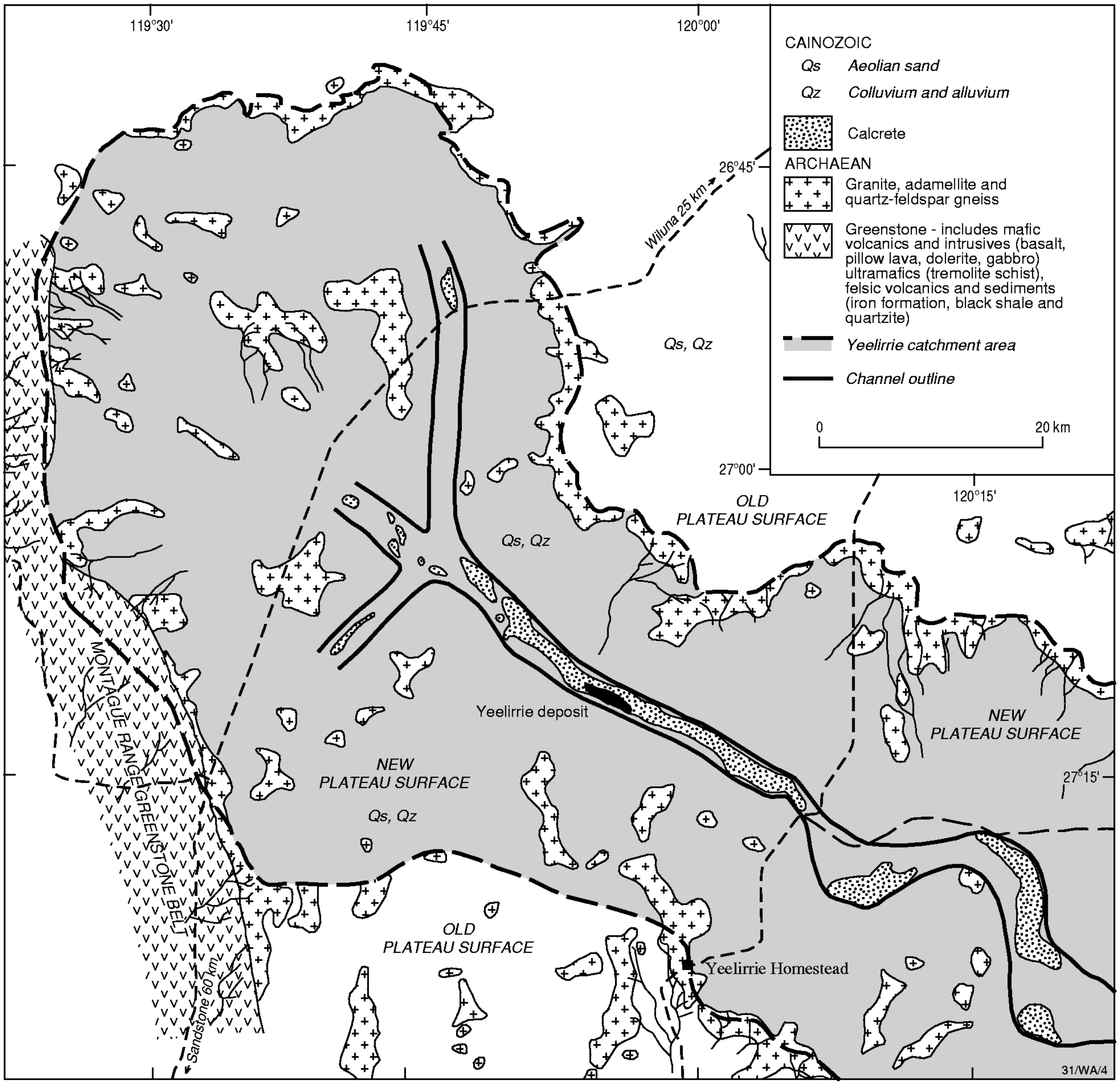

Figure 38. Regional geological setting of the Yeelirrie deposit (after Cameron, 1990)

porcellanous calcrete forms discrete, bulbous masses that commonly truncate the horizontal layering in the earthy calcrete, and appear to be growth mounds. The carbonate content in the porcellanous variety is commonly 70%, whereas the earthy variety has a much lower carbonate content.

The calcrete is underlain by the *clay–quartz unit* (alluvium), which extends down to decomposed basement. The boundary between the calcrete and the alluvium is transitional. The alluvium consists of red clay with disseminated detrital quartz grains and quartz-rich bands, thin seams of celestite, or thin arkose layers overlying the basement.

The uranium deposit is a horizontal sheet approximately 9 km long and up to 1.5 km wide. The bulk of the mineralisation is confined to the interval between 4 m and 8 m below surface, with approximately 90% below the water table. The average thickness of mineralised material assaying 0.10% U_3O_8 or greater is 3 m (Western Mining Corporation, 1978). Approximately 90% of the mineralisation is in a zone 4 m thick at the transition between the calcrete and the clay–quartz. Resources for the Yeelirrie deposit are shown in Table 20.

Table 20. Resource estimates for the Yeelirrie deposit (Western Mining Corporation, 1982)

	Grade range % U_3O_8	Ore (Mt)	Av. Grade % U_3O_8	U_3O_8 (t)
Prime ore	>0.15	13	0.24	32 000
Intermediate ore	0.05–0.15	22	0.09	20 500
Total proved ore reserves		35	0.15	52 500

The uranium mineralisation is carnotite, which occurs as a thin film coating cavities and fractures, or disseminated through the earthy calcrete.

WMC proposed to mine the deposit by open cut, either with scrapers and backhoes or bucket-wheel excavators. A 1 t/hour metallurgical research plant was commissioned at Kalgoorlie in late 1980 and a detailed feasibility study for production at the rate of 2500 t U_3O_8/year was completed in August 1982.

Lake Way deposit

The **Lake Way** deposit, 16 km south-east of Wiluna, is at the north-eastern margin of Lake Way (a playa feature) (Fig. 23). The deposit was discovered in 1972 during follow-up work on anomalies defined in an airborne radiometric survey by Delhi International Oil Corporation and Vam Limited (Brunt, 1990). Mineralisation is in earthy calcrete and clay in the lower reaches of a Tertiary drainage channel where it enters the north-east margin of Lake Way. Carnotite occurs on slickenside surfaces, on bedding planes, in clay-gravel, and as coatings on broken calcrete blocks at the water table–air interface, extending up to 1 m above the interface and down to 2 m below (Brian Lancaster & Associates, 1981). There are four areas of ore-grade mineralisation connected by areas of subeconomic mineralisation. The thickness of the mineralisation averages 1.5 m and varies from a maximum of 5 m down to a few centimetres. French and Allen (1984) stated that 'reserves' are 3300 t U_3O_8 at a cut-off grade of 0.065% U_3O_8. Planned production by Delhi International and Vam Limited was by open cut mining and treatment of ore by alkaline leaching, followed by resin-in-pulp ion exchange, to produce 500 t U_3O_8/year.

Lake Maitland deposit

At **Lake Maitland**, 102 km south-east of Wiluna, there are several uranium calcrete deposits (Fig. 23). The title 'Lake Maitland' was first applied by Cultus Pacific NL to two small zones of mineralisation. The best analysis was 0.06% U_3O_8 over 2 m and resources in these zones were assessed to be 500 t at an average grade of 0.04% U_3O_8 (Cultus Pacific NL, 1979).

The name 'Lake Maitland' is currently applied to another surficial deposit of carnotite mineralisation within calcrete at Lake Maitland that was evaluated by Carpentaria Exploration Company Pty Ltd (Cavaney, 1984), Esso and more recently by Acclaim Uranium NL (Acclaim Uranium NL, 1999). The deposit, previously known as **Mount Joel**, is located 105 km south-east of Wiluna. The deposit underlies the northern end of Lake Maitland and extends in an arcuate north–south zone around a siliceous calcrete delta on the western side of the lake with the two arms of the zone pointing to the west. The mineralised zone is about 6 km long and 300–600 m wide. The mineralisation is 1.5–2.0 m below the surface, and 0.2–2.0 m thick (maximum 3.75 m). The carnotite is mostly in slabby calcrete, but also in sand, clay and silt. The indicated and inferred ore resources within the Lake Maitland deposit were estimated to be 7863 t U_3O_8 at an average grade of 0.0518% U_3O_8 using a cut-off of 0.02% (200 ppm) U_3O_8 (Acclaim Uranium NL, 1999). Acclaim also calculated an indicated and inferred resource of 5016 t U_3O_8 at a higher cut-off of 0.05% U_3O_8 (500 ppm; Table 21).

Table 21. Resources for Lake Maitland (Acclaim Uranium, 1999)

	200 ppm U_3O_8 cut-off			500 ppm U_3O_8 cut-off		
	Resources (t)	Av. grade ppm U_3O_8	U_3O_8 (t)	Resources (t)	Av. grade ppm U_3O_8	U_3O_8 (t)
Indicated	4 865 000	593	2 886	3 191 000	705	2 250
Inferred	10 303 000	483	4 977	3 932 000	704	2 766
Total	15 168 000	518	7 863	7 123 000	704	5 016

Centipede deposit

Valley calcretes extend over a distance of 33 km in the Hinkler Well–Centipede (Fig. 23) drainage system (Crabb, Dudley & Mann, 1984), which enters the south-western side of Lake Way. In the western part of the system the valley calcrete is over 2 km wide, but it narrows to 0.5 km before broadening into a chemical delta on entering Lake Way. The thickness of the calcrete also decreases from 15 m to 5 m down-drainage. Carnotite mineralisation in the main valley calcrete is known as the **Hinkler Well** prospect, and the mineralisation in the chemical delta is known as the **Centipede** deposit. Isolated lenses of up to 0.01% U occur in the Hinkler Well area, and the main zone of 1 x 3 km is associated with carbonated weathered granite. The Centipede deposit comprises three distinct lenses of higher-grade mineralisation with carnotite present throughout the carbonate matrix. The mineralised zones are 1–5 m thick and are beneath 0–6 m of overburden (Brunt, 1990). At Centipede, a total of 3800 t U_3O_8 with an average grade of 0.1% U_3O_8 has been outlined by drilling (Brunt, 1990). The deposit is 12 km south of the Lake Way uranium deposit. Acclaim Uranium NL resumed exploration over the eastern portion of the Centipede deposits in the late 1990s and reported two separate resource bodies — Abercromby with 1755 t U_3O_8 at 0.07% and Millipede with 502 t U_3O_8 at 0.049% U_3O_8. Both resources were calculated at a cut-off grade of 0.02% U_3O_8. Acclaim also calculated these resources at a higher cut-off grade of 0.05% (Table 22).

Table 22. Resources for Abercromby and Millipede lenses of the Centipede deposit (Acclaim Uranium, 1999)

Abercromby (part of Centipede)	200 ppm U_3O_8 cut-off			500 ppm U_3O_8 cut-off		
	Resources (t)	Av. grade ppm U_3O_8	U_3O_8 (t)	Resources (t)	Av. grade ppm U_3O_8	U_3O_8 (t)
Measured	230 000	976	224	226 000	985	223
Indicated	815 000	889	725	605 000	1 056	639
Inferred	1 348 000	598	806	515 000	986	508
Total	2 393 000	700	1 755	1 346 000	1 020	1 370

Millipede (part of Centipede)	200 ppm U_3O_8 cut-off			500 ppm U_3O_8 cut-off		
	Resources (t)	Av. grade ppm U_3O_8	U_3O_8 (t)	Resources (t)	Av. grade ppm U_3O_8	U_3O_8 (t)
Measured	461 000	616	284	288 000	733	211
Indicated	305 000	416	127	57 000	719	41
Inferred	251 000	367	91	20 000	1 063	21
Total	1 017 000	490	502	365 000	750	273

Other deposits

At the **Dawson Well** prospect, 8 km west of Hinkler Well, uranium mineralisation occurs within the western upstream portion of the Centipede drainage channel. According to Acclaim, a large area contains uranium mineralisation up to 300 ppm U_3O_8, but no significant uranium deposits were identified.

The **Nowthanna** deposit lies 75 km south-south-east of Meekatharra and is located on the eastern shore of Quinn's Lake. The deposit was originally detected as an aerial radiometric anomaly and drilled by WMC in 1970. Acclaim Uranium NL carried out further drilling during 1998–99 and delineated an indicated resource of 4626 t U_3O_8 at a 0.02% U_3O_8 cut-off, and 2023 t U_3O_8 at a cut-off of 0.05% U_3O_8 (Table 23). The uranium is present as carnotite and is confined to the top 6–8 m of soil and calcrete, which overlies at least 60 m of lake clays (Cameron, 1991a).

Table 23. Resources for the Nowthanna deposit (including Nowthanna Joint Venture) (Acclaim Uranium, 1999)

	200 ppm U_3O_8 cut-off			500 ppm U_3O_8 cut-off		
	Resources (t)	Av. grade ppm U_3O_8	U_3O_8 (t)	Resources (t)	Av. grade ppm U_3O_8	U_3O_8 (t)
Indicated	10 368 451	446	4 624	2 367 189	855	2 024

At the **Lake Austin** deposit, 20 km west-south-west of Cue, the carnotite mineralisation is in a narrow arm of a playa at the termination of an extensive calcrete drainage system (Heath, 1980; Heath, Deutscher & Butt, 1984) (Fig. 23). The mineralised area is at the western edge of an extensive calcrete platform extending over an area of 50 km^2. The higher concentrations of uranium extend over an area of about 1500 m x 50 m with maximum values in excess of 0.2% U_3O_8. Mineralisation is mostly in the top 1–5 m, and the maximum concentrations are close to the water table. The carnotite forms patches and coatings in clay. Acclaim Uranium NL conducted drilling of Lake Austin in the late 1990s, and outlined the results in their 1999 annual report, as follows:

- In 1998, Acclaim drilled a mineralised uranium zone in a calcrete delta at the northern edge of Lake Austin and assessed a uranium resource of 240 t U_3O_8 at an average grade of 0.048% U_3O_8 (Table 24). This deposit is referred to by Acclaim as the 'Lakeside' deposit,
- The Wondinong prospect comprises several uraniferous calcrete trunk channels where they enter Lake Austin. According to Acclaim there is little potential for discovery of significant uranium deposits,
- The Anketell prospect is 100 km east of Mount Magnet township and occurs within a calcrete-filled trunk drainage channel that drains into Lake Austin. Carnotite mineralisation was intersected in widely spaced drill holes drilled in the 1970s.

Table 24. Resources for the Lake Austin (Lakeside) deposit (Acclaim Uranium, 1999)

	200 ppm U_3O_8 cut-off		
	Resources (t)	Av. grade ppm U_3O_8	U_3O_8 (t)
Unspecified	510 000	480	240

At **Thatcher Soak**, 250 km north-east of Leonora, the mineralisation extends over a length of 7.5 km (Fig. 23). It is 100–200 m wide and up to 2 m thick, and covered by shallow overburden averaging 1–2 m thick. The best ore sample analysis was 0.06% U_3O_8 over 2 m. Resources were estimated to be 4100 t U_3O_8 averaging 0.03% U_3O_8 (Cultus Pacific, 1979).

At **Lake Mason**, 150 km south-west of Wiluna, the mineralised area is 4.9 km long and 250–750 m wide (Fig. 23). The average thickness is less than 1 m, with mineralisation covered by 1–2 m of overburden. The best analysis was 0.08% U_3O_8 over 2 m. Resources were estimated to be 2700 t U_3O_8 with an average grade of 0.035% (Cultus Pacific, 1979). Renewed exploration drilling by Acclaim Uranium NL in the late 1990s failed to locate additional resources in this area.

The **Lake Raeside deposit**, 70 km west of Leonora, is in a low-lying peninsula on the northern side of the lake (Gamble, 1984) (Fig. 23). The uranium is in calcareous clay and clayey grit, mainly red or brown, overlying indurated ferruginous clay. The mineralised zone measures about 5.6 km long, 100–800 m wide and 1–2 m thick. The zone is between 1 m and 5 m below the surface and generally slightly above the water table. Gamble (1984) stated that at a cut-off grade of 0.02% U_3O_8, the resource is estimated to be 1700 t U_3O_8 at an average of 0.025% U_3O_8. This is based mainly on radiometric probing of drill holes on a 200 m x 200 m grid, which Gamble (1984) considered inadequate for preparing a satisfactory resource estimate.

Joint-venture partners in a Yeelirrie project drilled several other small calcrete uranium deposits in the Yilgarn Block during the early 1970s. These include **Windimurra**, 200 km south-west of Yeelirrie; **Cogla Downs**, 125 km west of Yeelirrie; and **Murchison Downs**, 115 km west-north-west of Yeelirrie. According to later exploration results obtained by Acclaim Uranium NL during the late 1990s, there was little chance of locating large economic resources in the Cogla Downs calcrete channels (Acclaim Uranium NL, 1999).

CALCRETE DEPOSITS OUTSIDE THE YILGARN CRATON

In the Gascoyne Complex, small uranium deposits in Tertiary calcrete overlying Proterozoic granite and metamorphics include **Minindi Creek**, 250 km east of Carnarvon (Fig. 23), **Jailor Bore**, 200 km north-east of Carnarvon, and **Lamil Hills**, at Lake Waukarlycarly, 200 km east-north-east of Nullagine (Muggeridge, 1980).

Cooper and others (1998) noted widespread calcrete-hosted uranium occurrences in a belt along the south-west contact of the Bangemall Basin with the older Gascoyne Complex rocks. The source of uranium in the calcrete deposits is attributed to the basement rocks. The calcrete deposits have developed both over the Gascoyne Complex and over the lower part of the Bangemall Group in close proximity to the unconformity with the Gascoyne Complex. The Telfer South prospect is the most significant of these occurrences and the mineralisation is in the lower part of the Bangemall Group in siltstone underlying massive dolomite of the Irregully Formation. The mineralisation in Tertiary groundwater channels is carnotite, as fracture coatings and cavity fillings in siltstone of the Irregully Formation, and the mineralisation is enhanced by increased density of fracturing. The mineralised zone measures 400 m x 100 m in a topographic depression around the Telfer granite that preferentially collects uranium-bearing rainwater from the granite.

Calcrete-type uranium mineralisation has also been reported south of the Ngalia Basin, Northern Territory (Fig. 35) (Stewart, 1982). At several localities, carnotite is known to occur in channel calcrete and calcareous sand in the Tertiary drainages that cross the Stuart Bluff Range. The low-grade **Napperby** deposit trends north-east, and is several kilometres long by 1500 m wide (Akin & Bianconi, 1984). The mineralised layer is 1–3 m thick and is at a shallow depth in calcareous clayey sand overlain by calcareous sediment. The uranium minerals are carnotite and minor amounts of tyuyamunite. Another calcrete-type uranium deposit, **Currinya**, 120 km west of the Napperby deposit, is near the southern edge of the Ngalia Basin. Carnotite occurs in Quaternary calcrete and sandy clay. The mineralisation is patchy and discontinuous and grades are low.

METASOMATITE DEPOSITS

Metasomatite deposits in Australia occur only in the Mount Isa Inlier, north-west Queensland.

MOUNT ISA URANIUM FIELD

The following summary of the history of uranium exploration in the Mount Isa region covers exploration in both the Mount Isa and Mary Kathleen uranium fields (Battey & others, 1987; Morwood & Denaro, 2000). The regional geology and ore deposits in these two fields are described separately in this and the next chapter. Mary Kathleen is a metamorphic deposit.

There was a period of intensive exploration for uranium in the Palaeoproterozoic rocks of the Mount Isa Inlier (Fig. 39) from 1954 to 1956. The first discovery, at Skal, 32 km north of Mount Isa, was made by a prospector in early 1954 (Brooks, 1975). Anderson's Lode and the Valhalla deposit were also discovered by prospectors in 1954, and in July of that year prospectors discovered the Mary Kathleen deposit. In 1954, Mount Isa Mines Ltd (MIM) completed an airborne scintillometer survey over the Eastern Creek Volcanics and other basic volcanics. Rio Tinto Australian Exploration Pty Ltd carried out airborne surveys over the Corella Formation (Searl & McCarthy, 1958) and BMR similarly surveyed the contact zones of granite intrusions (Parkinson, 1956). There have been no significant new discoveries in the region since 1954.

A second period of active exploration occurred between 1967 and 1971. Drilling was carried out by Mary Kathleen Uranium Ltd (MKU) at Mary Kathleen, and by Queensland Mines Ltd (QML) at Anderson's Lode, Valhalla, Skal, and several small deposits in the Calton Hills (Watta, Warwai deposits), Paroo Creek and Spear Creek areas (Queensland Mines Ltd, 1968, 1969a,b,c, 1970).

In a third period of active exploration from 1979 to 1982, MKU mounted another major program to locate and/or delineate further ore for treatment at Mary Kathleen, anticipating the exhaustion of economic reserves at the Mary Kathleen deposit. Deposits drilled included Elaine, Rita, Rary, Turpentine, Flat Tyre and Emancipation. In 1974, Agip Australia Pty Ltd bought a large number of mining leases from QML and private owners. These leases covered approximately 30 small deposits in the Eastern Creek Volcanics. From 1974 to 1981, Agip drilled many of these to test the depth and strike continuity of the mineralisation. Several companies carried out regional radiometric surveys and then tested the anomalies detected. Exploration was also carried out in Tertiary sands near the margins of the Mount Isa Inlier.

From 1993 to 1999, Summit Resources NL, in joint venture with Resolute Ltd, completed a major drilling program at the Valhalla deposit. This delineated significant extensions of the mineralisation to depths of more than 500 m below surface (see later description of Valhalla deposit).

From 1993 to 1995, North Ltd explored for Olympic Dam-style Cu–U–Au mineralisation in hematite breccia zones within Eastern Creek Volcanics in the general region adjacent to the Sybella Granite. This failed to locate significant mineralisation.

The Mary Kathleen deposit was the only deposit in the Mount Isa Inlier to be developed for production. Underground development and stockpiling of ore were carried out at the Flat Tyre and Mothers Day deposits, but these deposits were not developed further. The development of many deposits in the Mount Isa Inlier was inhibited by the refractory nature of the mineralisation. Summit Resources is currently investigating the feasibility of mining the Valhalla deposit. New metallurgical techniques to process the ore and recover uranium are also being investigated.

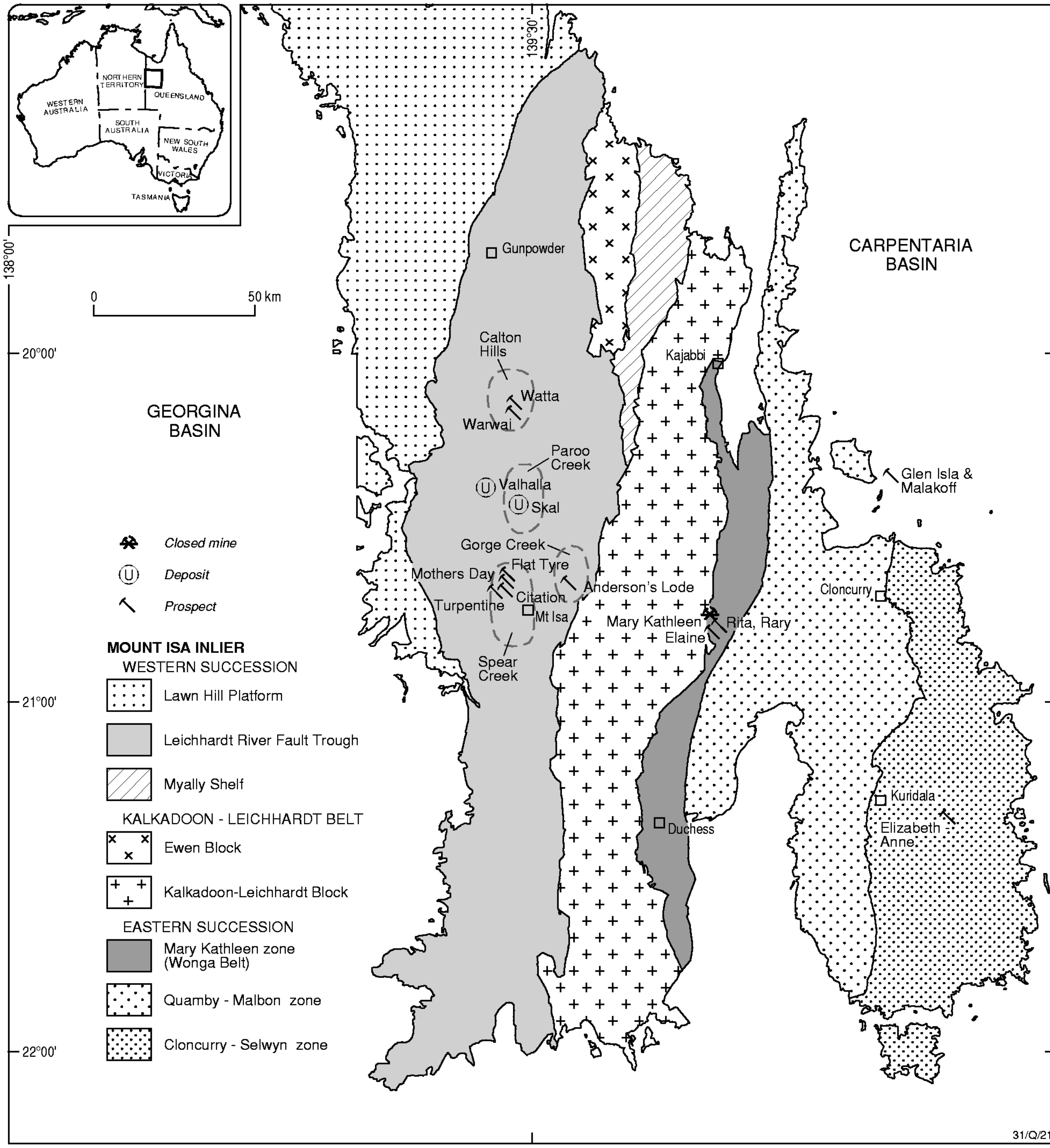

Figure 39. Regional geology of the Mount Isa Inlier and principal uranium deposits and prospects

Regional geological setting

The Mount Isa Inlier was remapped by BMR from 1969 to 1980 (Derrick, 1980; Plumb, Derrick & Wilson, 1980; Blake, 1987; Blake & others, 1990). From 1983 to 1989, BMR completed detailed structural, petrological and geochronological studies of the Mount Isa Inlier (Stewart & Blake, 1992). From 1995 onwards, AGSO, in conjunction with the Geological Survey of Queensland, the Northern Territory Geological Survey and research groups from a number of universities completed the Northern Australian Basin Resource Evaluation Project. This study established, inter alia, a regional time–space framework for the western portion of the Mount Isa Inlier.

The Mount Isa Inlier is subdivided by major north-striking faults into three broad tectonic belts (Fig. 39) — Western Succession, Kalkadoon–Leichhardt Belt and Eastern Succession. These comprise Palaeoproterozoic metasediments, volcanics and intrusive rocks. The Western Succession consists of the Lawn Hill Platform, Leichhardt River Fault Trough and the Myally Shelf. The Kalkadoon–Leichhardt Belt is bounded to the west and east, respectively, by the Quilalar and Pilgrim Fault zones. This belt comprises the Ewen Block and the Kalkadoon–Leichhardt Block. The Eastern Succession is subdivided into the Mary Kathleen zone in the west, the Quamby–Malbon zone, and the Cloncurry–Selwyn zone in the east (Blake, 1987; L. Hutton, Queensland Geological Survey, personal communication, 2001).

The basement rocks are a sequence of sedimentary, volcanic and intrusive rocks that was highly deformed during the 1900–1870 Ma Barramundi Orogeny. They are overlain by three 'cover sequences', which are Palaeoproterozoic volcano-sedimentary packages separated by regional unconformities (Blake, 1987). The cover sequences were deformed and regionally metamorphosed up to upper amphibolite facies during the 1620–1520 Ma Isan Orogeny.

The Mount Isa Inlier has been intruded by granitic batholiths of Palaeoproterozoic and Mesoproterozoic age.

The Leichhardt River Fault Trough is a palaeotectonic trough containing thick sequences of basalt and shallow-water sedimentary rocks now folded, faulted and regionally metamorphosed. A total of 107 uranium occurrences have been recorded in Palaeoproterozoic metasediments of the Leichhardt River Fault Trough. Most of these occurrences are in the Eastern Creek Volcanics; a few minor prospects are in the underlying Leander Quartzite. Brooks (1960, 1972, 1975) has described the geology and mineralogy of these stratabound prospects, which typically form steeply dipping tabular to pipe-like bodies and are often associated with breccia zones within the host rocks.

There are five principal host rock types: (1) tuff (Valhalla, Watta and Warwai); (2) shale and siltstone (Valhalla, Skal); (3) greywacke (Anderson's Lode); (4) hornblende–allanite schist (many small deposits in the Spear Creek area — the schist is probably metamorphosed basic volcanics); and (5) basalt (Surprise). Basic volcanics are associated with virtually all deposits in the Eastern Creek Volcanics; sedimentary host rocks are interbedded with the volcanics. The primary uranium mineral is fine-grained disseminated brannerite, commonly associated with magnetite or hematite, and in places with sphene, biotite, rutile, ilmenite and zircon. Secondary calcite and dolomite are present in the gangue (relevant when considering a leaching process for metallurgical extraction of uranium from these ores). Minor pyrite and chalcopyrite have been recorded. The secondary uranium minerals are metatorbernite, uranophane and carnotite.

Of the 107 uranium prospects recorded, approximately 41 have been drilled in four main areas — Spear Creek, Gorge Creek, Paroo Creek and Calton Hills. The largest deposits are Valhalla, Skal and Anderson's Lode.

In the Leichhardt River Fault Trough, the uranium deposits are metasomatite type deposits, whereas the uranium deposits in the Mary Kathleen zone are metamorphic type deposits (skarn-hosted metamorphic hydrothermal deposits).

Valhalla deposit

The **Valhalla** uranium–vanadium deposit, 40 km north of Mount Isa, was discovered by prospectors in 1954. United Uranium NL sank a 14 m deep shaft and drilled one hole to test the mineralisation. In 1968, Queensland Mines Ltd was granted a lease over the deposit, and in 1969 it commenced a program of mapping and radiometric surveys. During 1969 and 1970 the company drilled a total of 115 percussion holes and 35 diamond drill cored holes into the main Valhalla deposit and the smaller Valhalla South deposit. This drilling tested the deposit down to a depth of approximately 100 m below surface. The mineralisation continued below the deepest intersections.

The uranium mineralisation is refractory and there is a high proportion of calcite in the gangue; hence the uranium cannot be recovered by normal acid leach processing. Queensland Mines Ltd carried out metallurgical testwork using a range of processes including ore flotation followed by alkaline leaching of the flotation concentrates, and acid leaching of the tails. However, the results were disappointing because of poor recoveries and high processing costs.

Queensland Mines Ltd relinquished its mining leases in 1991. In 1992, Summit Resources NL applied for exploration tenements covering the deposit and surrounding area. These were granted in 1993. From 1993 to 1999, Summit in partnership with Resolute Ltd completed a program of percussion and diamond drilling mainly directed at testing the main deposit below the old drilling and down to depths of 500 m below surface. The results showed that the mineralised zone plunges south at 50° and that grades increase to around 0.2% U_3O_8 at depths of more than 200 m below surface. Some intersections average around 0.5%. The mineralisation is open at depth and the down-plunge continuation of the mineralisation has not been tested below 500 m. Consequently there is potential for additional resources to be found. In 2000, the company began a feasibility study to investigate the possibility of mining the deposit.

The Valhalla deposit occurs within a series of brecciated metasediments (mainly laminated carbonaceous shale and mafic tuff) and altered basalts (Eggers, 1999) which are part of the Palaeoproterozoic Eastern Creek Volcanics. The 1670 Ma Sybella Granite (Blake, 1987) outcrops 10 km south-west of the deposit. The deposit is located along the projected trend of the Mount Isa Fault zone and the brecciation of the host rocks may be related to this fault.

Mineralisation forms two tabular, vertically dipping zones striking north–south. The bulk of the mineralisation is in the main zone (Valhalla) which extends for 675 m at the surface and plunges 50°S. A much smaller zone, known as Valhalla South, occurs 1200 m to the south.

Uranium–vanadium mineralisation is confined to zones of red-coloured hematite–magnetite–carbonate alteration within the brecciated shales and tuffaceous sediments (Eggers, 1999). Sodic metasomatism and albitites are ubiquitous. Higher-grade uranium mineralisation is coincident with the presence of sodic pyroxenes (aegerine) and sodic amphiboles (arfvedsonite).

The uranium is in brannerite and to a lesser extent in uraniferous zircon — both these minerals are refractory (Henley, Cooper & Kelly, 1972; Eggers, 1999). Vanadium and minor copper mineralisation are present. Secondary uranium minerals in the weathered zone are metatorbernite, uranophane and carnotite.

Resources

In 1998 the analytical laboratory that assayed the drill core samples advised the company that systematic errors (bias) had occurred in the uranium assay procedures. Consequently, all the drill core samples from the holes drilled by Summit were re-assayed. Using the new assay results, the resources were recalculated at a cut-off grade of 0.08% U_3O_8 (Table 25).

Table 25. Resource estimates for the Valhalla deposit, March 1999 (Eggers, 1999)

	Resources (Mt)	**Grade (% U_3O_8)**	**U_3O_8 (t)**
Measured resources	4.016	0.15	6 024
Indicated resources	4.778	0.144	6 880
Inferred resources	2.687	0.135	3 627
Total	11.481	0.144	16 531

Vanadium resources have not been estimated, but Eggers (1999) reported that vanadium grades of around 1.3 kg/t V_2O_5 (0.13% V_2O_5) are associated with the uranium mineralisation.

Genesis

The mineralisation appears to have been deposited from hydrothermal fluids that produced the sodic alteration and hematite–magnetite–calcite alteration. These fluids and the uranium mineralisation are related either to a magmatic event (yet to be dated) or to regional sodic- and hematite-rich metamorphic alteration which is known to be widespread in the Mount Isa Inlier. This cannot be resolved because detailed studies and age dating to determine the origin of the deposit have not been undertaken. The geology and mineralogy of the Valhalla deposit are similar to those of the Zhelty Vody deposit in the Krivoy Rog area of Ukraine (Dahlkamp, 1993), which is a metasomatite deposit in metasomatised sediments. Consequently, it is proposed that Valhalla is a metasomatite deposit.

Metallurgy

Summit Resources carried out metallurgical testwork on drill core sample material. Radiometric sorting of the ore was trialled and the results showed that this process could successfully upgrade the ore. The higher-grade ore from the ore-sorting process was ground and treated by normal flotation, and the flotation concentrates were processed by a two-stage acid leach at high temperatures (250°C) and pressures. Recoveries of around 90% have been achieved by this processing (Eggers, 1999). Similar testwork is proposed for the Skal and Anderson's Lode deposits, which have mineralogy similar to that of Valhalla.

Other deposits

The **Skal** deposit, 35 km north of Mount Isa, was tested in 1954 by Mount Isa Mines Ltd. Queensland Mines Ltd bought the leases in 1959 and carried out drilling in 1959–60 and again in 1968–69. Finely disseminated brannerite (in association with magnetite or hematite, calcite and minor chalcopyrite and pyrite) occurs in a brecciated siltstone interbedded with basic volcanics (Brooks, 1975). The southern zone measures 152 m x 18 m and the northern zone 120 m x 23 m. Queensland Mines Ltd (1973) reported possible resources of 3447 t U_3O_8, in resources averaging 0.13% U_3O_8, using a cut-off grade of 0.05% U_3O_8. Summit Resources NL acquired exploration tenements over the deposit in 1993. The company re-assessed the mineral resources using the QML drill hole data and reported that the 'identified mineral resources' were 2 712 000 t averaging 0.13% U_3O_8, representing 3450 t U_3O_8 (Summit Resources, 1998).

Anderson's Lode (Counter deposit), 14 km north-east of Mount Isa, is in a lens of altered greywacke interbedded with altered basalt. Dolerite dykes occupy transverse faults and form the eastern and western limits of the mineralisation. In outcrop the deposit is 46 m long and 17 m wide (Brooks, 1960). Gangue minerals include hematite, ilmenite, calcite, sphene and rutile. Queensland Mines Ltd (1973) reported that probable resources, at a cut-off grade of 0.1% U_3O_8, total 1179 t U_3O_8, averaging 0.20%. Summit Resources NL acquired the deposit in 1993, re-assessed the mineral resources using the existing drill hole data, and reported 'identified mineral resources' of 1 240 000 t averaging 0.167% U_3O_8, representing 2100 t U_3O_8 (Summit Resources, 1998).

The many small deposits in the Spear Creek area are hosted by amphibolite and hornblende–allanite schist (metamorphosed basalt). The primary mineral is uraninite. These prospects were tested by MIM and subsequently by QML prior to 1971. From 1979 to 1980, Urangesellschaft Australia Pty Ltd drilled **Turpentine** and **Folderol** (5 km north-east of Turpentine) (Gooday & McKinnon-Love, 1980). In 1980, Kelvin Energy drilled the **Ardmore East** prospect, 90 km south of Mount Isa (Chan, 1981). In 1980–81, MKU explored and drilled the **Turpentine**, **Flat Tyre**, **Citation** and **Emancipation** prospects.

The **Watta** and **Warwai** prospects (Calton Hills area) are in metamorphosed acid tuff interbedded with pelitic metamorphics of the Leander Quartzite.

The **Miranda** prospect is in chlorite schist of the Kalkadoon–Leichhardt Block (Allnutt & Scott, 1983).

METAMORPHIC DEPOSITS

The Mount Isa Inlier, north-west Queensland, contains Australia's only metamorphic deposits of uranium, at the Mary Kathleen uranium field.

MARY KATHLEEN URANIUM FIELD

The Mary Kathleen orebody was discovered in July 1954. The history of uranium exploration in the Mary Kathleen uranium field is described in the previous chapter, under 'Mount Isa uranium field'.

Regional geological setting

The Mary Kathleen zone (Fig. 39) is a sequence of shallow-water shelf sediments that have undergone complex folding, regional metamorphism, and granitic intrusion and metasomatism. These metasediments are Palaeoproterozoic and the zone is approximately 10–20 km wide and more than 200 km long.

In the Mary Kathleen zone there are several uranium deposits in metasediments and skarns of the Palaeoproterozoic Corella Formation. Mary Kathleen is the largest and there are about 40 minor prospects, mainly up to 20 km to the north-east and south of it (Brooks, 1975). There are also some minor deposits east and south of Cloncurry, in the Soldier's Cap Formation, Marimo Slate and Kuridala Formation.

Several felsic and mafic bodies intrude the Corella Formation. The largest is the foliated, coarse-grained Burstall Granite, whose western margin is cut by a network of microgranite and porphyritic rhyolite dykes. The extensive Lunch Creek Gabbro flanks the Burstall Granite on its eastern side.

Mary Kathleen deposit

The **Mary Kathleen** uranium–rare earth element (REE) deposit lies in the Mary Kathleen zone and is hosted by metamorphic rocks of the Palaeoproterozoic Corella Formation. The Corella Formation, which has been dated at 1780–1760 Ma, is mainly contact and regionally metamorphosed evaporitic calc-silicate rocks with marble, metapelites, metasammites and minor metavolcanics.

In the Palaeoproterozoic metasediments of the Mary Kathleen zone, four phases of deformation-related hydrothermal activity are recognised that occurred over a time range from at least 1750 Ma to 1100 Ma. Intense metasomatism occurred during all four phases, caused by reactions with highly saline fluids derived in part from the evaporitic Corella Formation sediments.

The first phase of metamorphism and deformation (phase 1) of the Mary Kathleen zone was accompanied by widespread emplacement of granitic and mafic bodies, contact metamorphism and metasomatism (Holcombe, Pearson & Oliver, 1991, 1992; Oliver & others, 1991). Intrusion of granitic and mafic bodies occurred between 1750 and 1730 Ma. They include the Burstall Granite dated at 1737 ± 15 Ma (Page, 1983; Pearson, Holcombe & Page, 1992). Sediments in the vicinity of the Burstall Granite were contact metamorphosed and large garnet–pyroxene skarn bodies formed during this phase. These skarns formed in the extensive hydrothermal systems that developed by interaction between voluminous, volatile-rich intrusions and the calc-silicate and evaporite country rocks (Oliver & others, 1999).

A second phase of metamorphism and deformation (phase 2) which reached a peak metamorphic grade of upper amphibolite facies was accompanied by a renewed phase of hydrothermal activity between 1550 and 1500 Ma. Intense scapolitisation of the Corella Formation metasediments during this second phase of deformation and metamorphism implies that the fluids were highly saline and this is supported by the presence of such fluids in inclusions (Oliver & Wall, 1987).

The Mary Kathleen deposit occurs in the axial surface of a tight syncline (the Mary Kathleen Syncline), which formed during the second phase of deformation (Fig. 40). The western limb of this syncline is cut by the Mary Kathleen shear zone, and the eastern limb by the Burstall Granite. Slightly younger rhyolite dykes west of the granite have similar compositions and an identical radiometric age. The Burstall Granite and the rhyolite dykes have elevated uranium and thorium contents.

The main rock types in the syncline are hornfelsed calc-silicate rocks, skarn, cobble conglomerate, 'igneous textured granofels', diorite, calc-silicate granofels, quartzite, amphibolite and impure marble (Scott & Scott, 1985).

The diorite is 50–100 m thick and includes several basic rock types; it occurs along the east limb and keel of the syncline. At the same stratigraphic position on the west limb there is a fine-grained, grey feldspar–diopside granofels with relict igneous textures (Scott & Scott, 1985).

Mary Kathleen Shear Zone

The Mary Kathleen shear zone (Fig. 40) has a north–south regional trend and is approximately parallel to the axial trace of the Mary Kathleen Syncline, except in the vicinity of the orebody. Here the shear zone wraps around the skarn to form a bulge, in a departure from its regional trend. Exposures in the open cut show that the shear zone truncates the skarn host to the orebody, and skarns are absent to the west of the shear zone. However, the shear does not truncate ore zones (Oliver & others, 1999). Most of the vertical movement along the shear zone occurred late in the second phase of regional metamorphism.

Skarns

The skarns and metamorphosed carbonates along the eastern limb of the Mary Kathleen Syncline were formed during emplacement of the Burstall Granite. The age of these phase 1 skarns is 1766 ± 80 Ma, which overlaps that of the granite (Cruikshank, Ferguson & Derrick, 1980; Maas & others, 1987). At the Mary Kathleen deposit and Elaine prospect, metamorphosed carbonates typically contain calcite, mostly andradite garnet, clinopyroxene, wollastonite, K-feldspar and minor scapolite with uranium and REE. Maas and others (1987) concluded that uranium and REE enrichment also occurred at this time (1766 ± 80 Ma) in the skarn at or near the present orebody.

Approximately 200–250 Ma later, metasomatism associated with phase 2 deformation and intrusion produced a second generation of skarns containing andradite garnet, K-feldspar, albite, epidote, scapolite and ferrohastingsite together with uranium and REE mineralisation (Derrick, 1977). There was widespread garnet veining and replacement of previous skarn mineral assemblages.

Age dating of uraninite has yielded 1550 ± 15 Ma (Page, 1983), which is approximately the same age as the second phase of deformation. Field relationships indicate that ore formation occurred after the folding but was synchronous with or predated shearing on the Mary Kathleen shear under amphibolite facies metamorphism (Oliver & others, 1990). Brecciation and reworking of earlier skarns took place during phase 2 skarn formation. During this phase, the previously existing uranium–REE mineralisation may have been reworked and possibly upgraded.

Mineralisation

Uranium–REE mineralisation occurs within the skarn and is surrounded by an extensive irregular alteration zone consisting mainly of garnet (andradite–grossularite) with lesser amounts of diopside, scapolite and feldspar. Where alteration is incomplete, garnet and diopside form veins and lit-par-lit

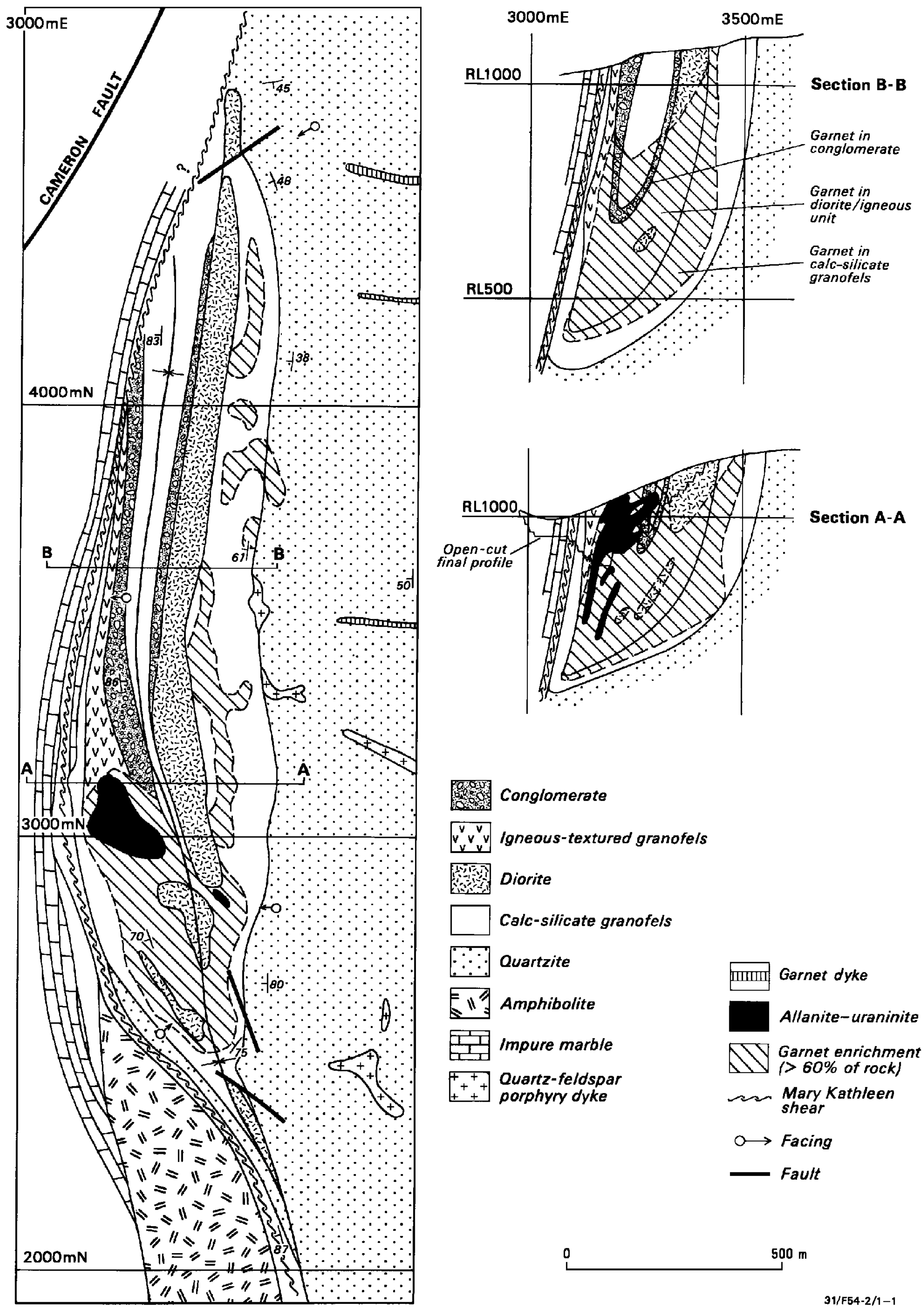

Figure 40. Geology of the Mary Kathleen deposit (after Scott & Scott, 1985)

injections. In the centre of the orebody, alteration is virtually complete and only small remnants of altered diorite and cobble conglomerate remain (Mary Kathleen Company Geologists, 1981).

The uranium–REE mineralisation formed in the alteration zone; but the original stratigraphy affected its distribution. About 80% of the ore was precipitated in altered diorite, which appears to have been a favourable host rock, and the rest was precipitated in altered cobble conglomerate (Scott & Scott, 1985).

The mineralisation changes gradually with depth. Down to about 100 m the orebody consists of several large irregular lenses of high-grade ore dipping at 30–50°W and extending over a zone up to 100 m wide. With increasing depth, the lenses become a series of narrow, irregular, steep zones subparallel to the Mary Kathleen Shear.

Large irregular zones of allanite (a complex rare-earth silicate) occur in a honeycomb pattern throughout the alteration zone. Uraninite is disseminated throughout the allanite zones as ovoid grains 0.01–0.1 mm across; most of them are surrounded by a thin shell of silica, pyrite, or radiogenic galena (Mary Kathleen Company Geologists, 1981). Other gangue minerals include hornblende, prehnite and calcite. Sulphides occur as irregular pods of massive sulphide and as disseminations. The cores of the massive sulphide pods contain up to 95% pyrrhotite, with minor chalcopyrite, diopside, allanite and garnet. The pods are rimmed by narrow zones of disseminated pyrrhotite and chalcopyrite. Minor amounts of pyrite, marcasite, galena, sphalerite, molybdenite, pentlandite, bornite and linnaeite are also present. Although sulphides are locally abundant, the average sulphide content of the orebody is only about 2%.

The main REE are lanthanum and cerium, which comprise about 85% of the rare-earth content (Hawkins, 1975).

Mass and others (1987) proposed that the orebody formed during phase 2 skarn development and that the higher grade U-REE ore formed by enrichment of an earlier-formed low-grade mineralisation. The earlier mineralisation formed during the development of phase 1 skarns, which were produced by high temperature metamorphism and metasomatism of the Corella Formation during intrusion of the Burstall Granite. The granite is fractionated, oxidised and uranium-rich with an average content of 7–10 ppm U. The reworking of the skarns during phase 2 deformation was associated with shearing and was also associated with oxidising fluids with high salt contents derived from evaporitic minerals in the Corella Formation.

Oliver and others (1990, 1999) have proposed an alternative origin for the deposit, whereby reworking of the skarn occurred during phase 2 deformation, with large-scale fluid circulation introducing uranium and rare-earth mineralisation from an external source via the Mary Kathleen shear.

In summary, Mary Kathleen is considered to be *a skarn-hosted metamorphic–hydrothermal deposit.*

Resources

The total resources within the orebody before mining started were estimated to be 9 483 000 t ore averaging 0.131% U_3O_8 (Hawkins, 1975), i.e. an initial resource of 12 000 t U_3O_8.

Mining of the Mary Kathleen orebody took place in two periods: 1958 to 1963, and 1976 to 1982. Total production during these periods was 7532 t U (8882 t U_3O_8). After mining ended, the resources below the open cut were estimated to be 1018 t U (1200 t U_3O_8) (Mary Kathleen Uranium Ltd, 1981). The company reported that this could not be extracted at a profit because of the high mining costs involved and the low prices for spot-market sales at that time.

Other deposits in the Mary Kathleen zone

Uranium prospects in the Mary Kathleen Syncline include the Rita, Rary and Elaine prospects, which have been drilled intermittently by Mary Kathleen Uranium Ltd since the late 1960s, mainly from 1979 to 1981 (Scott, 1981, 1982). In the **Rita**–**Rary** area, both concordant and discordant mineralisation occur over a strike length of 1300 m. Thin discontinuous bands of allanite/uraninite occur in a dark green garnet–diopside–amphibole rock of possible volcanic origin. Also, discordant veins of allanite and uraninite cut garnet-rich calc-silicate rocks along the margins of a dolerite dyke (Scott & Scott, 1985). At the **Elaine** prospect, mineralisation occurs within conformable bands of allanite–diopside up to 1 m thick in banded feldspar–scapolite–diopside–garnet granofels. The in situ resources at Elaine amount to 100 t U_3O_8 at an average grade of 0.06% (Scott, 1982).

The **Elizabeth-Anne** prospect, 10 km east-south-east of Kuridala, lies in the Cloncurry–Selwyn zone. Uraninite–brannerite mineralisation fills fractures in a banded iron formation where this unit has been intruded by a dolerite dyke (Donchak & others, 1983; Hoskins & Scott, 1983).

VOLCANIC DEPOSITS

The Georgetown–Townsville uranium field contains the only volcanic deposits of uranium in Australia, with Ben Lomond and Maureen being the main deposits in this field.

GEORGETOWN–TOWNSVILLE URANIUM FIELD

Central Coast Exploration NL began work in the Georgetown area (Fig. 41) in 1969 (O'Rourke, 1975). Initially the work was directed at assessing the base-metal potential, but as exploration progressed, the company decided to include uranium. Airborne radiometric and magnetic surveys carried out in July 1971 led to the discovery of outcrops of the Maureen deposit; the first holes were drilled in 1972. The discovery led to a rapid increase in uranium exploration throughout the Georgetown Inlier from 1972 to 1979 which spread progressively southwards, covering areas of Carboniferous acid volcanics as far south as Townsville.

Dolphin Exploration discovered uranium mineralisation at the Lineament Group prospects (Fig. 41), near Mount Turner, in the late 1970s. At the Central 50 prospect (Lineament Group), uranium mineralisation is adjacent to a dolerite dyke and the company drilled this mineralisation over a strike length of 170 m and down to a depth of 200 m.

Union Carbide (Australia) explored the basal sediments of the Newcastle Range Volcanic Group near Dagworth and found minor mineralisation. In 1971, Pioneer Mining & Exploration Pty Ltd drilled the Laura Jean prospect in these volcanics. Pechiney (Australia) Exploration carried out an extensive exploration program in the Newcastle Range Volcanic Group during the 1970s, detecting numerous anomalies by an airborne radiometric and magnetic survey. The anomalies were further tested by detailed ground radiometrics and drilling. Uranium mineralisation was found to be widespread in clastic sediments at the base of the Newcastle Range Volcanics. Zones of mineralisation were drilled at the Trident and Twogee prospects (Crane, 1983). Minatome Australia continued exploration of these prospects from 1979 to 1982, and found them to be small.

In the Georgetown area, Minatome Australia Pty Ltd began exploration in 1971. Airborne radiometric and magnetic surveys were flown over selected areas of acid volcanics, and by 1975 this company also was exploring south to the Burdekin Basin south-west of Townsville. In June 1975, radiometric anomalies were recorded in flights along the northern portions of the St James Volcanics over what is now known as the Ben Lomond deposit (Valsardieu, Cocquio & Bauchau, 1980). In 1976 the first holes were drilled into the deposit. Detailed drilling and evaluation continued until 1982.

Further detail on uranium exploration by various companies in the Newcastle Range Volcanics and the Georgetown region is given in Withnall (1976) and Withnall and others (1997).

Regional geological setting

The regional geology of north Queensland is described in detail in a report and atlas (Bain & Draper, 1997a,b; Bain & Haipola, 1997) prepared as part of the National Geological Mapping Accord, North Queensland Project (a joint AGSO–Geological Survey of Queensland project). Previous descriptions of the regional geology were by Wyatt and others (1970), Henderson (1980), Withnall, Bain and Rubenach (1980), Levingston (1981), Blake (1982) and Bain and others (1983, 1990).

Proterozoic metasediments and metavolcanics of the Georgetown Inlier occupy much of the western part of the Georgetown–Townsville region. They are mainly mica schist, biotite gneiss, quartzite and pegmatite. Phyllite and slate occur in the low-grade metamorphic areas. The metamorphics have been

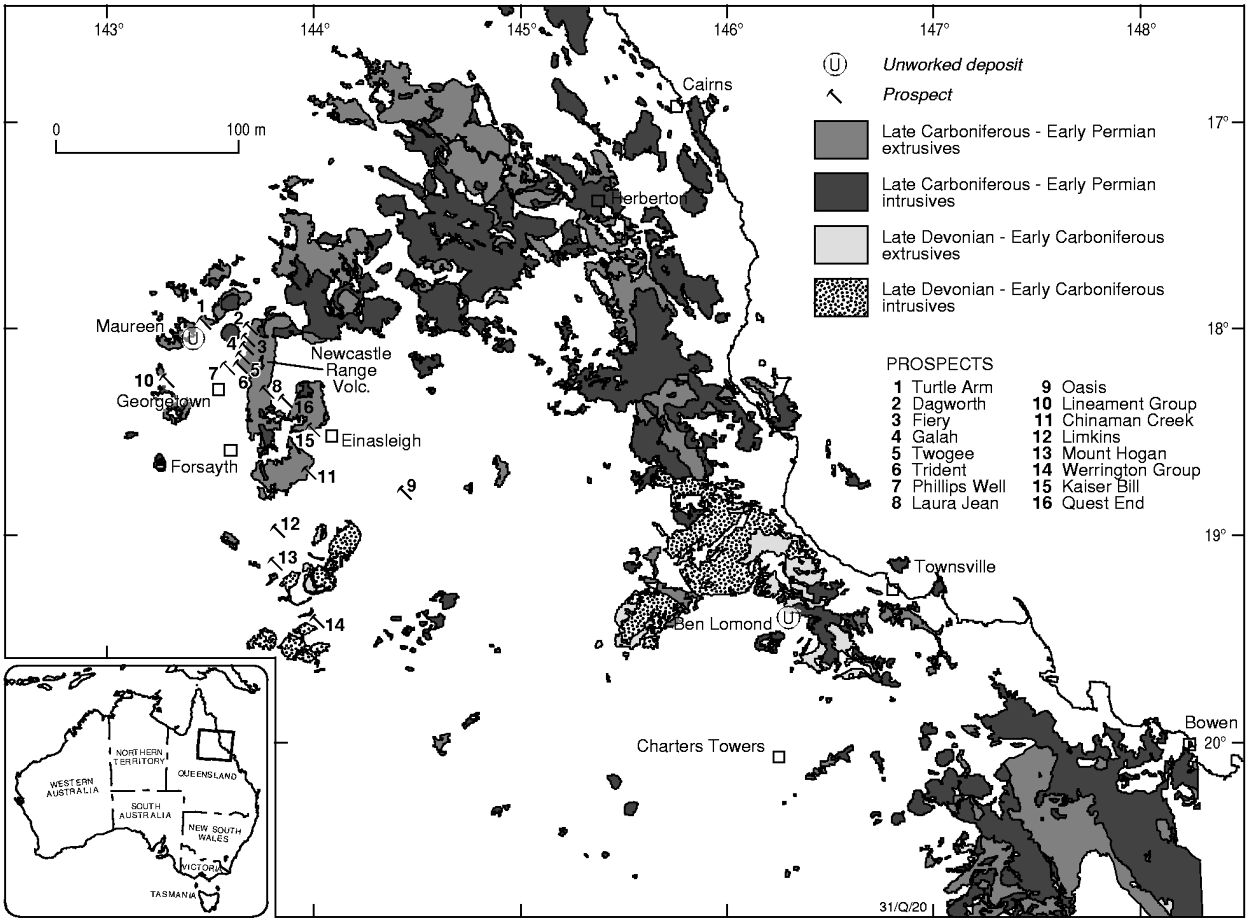

Figure 41. Granitoids, volcanics, and uranium deposits and prospects in the late Palaeozoic acid volcanic province, Georgetown–Townsville uranium field (after Bain & Draper, 1997a,b)

intruded by Proterozoic S-type and Siluro–Devonian I-type batholiths. Silurian and Devonian sediments of the Hodgkinson Province and Broken River Province occur in the eastern part of the Georgetown–Townsville region.

The late Palaeozoic acid volcanic province (Fig. 41), to which the uranium deposits are related, extends over a large area and comprises many comagmatic acid volcanic complexes, ring-dykes, granitoids and areas of related hydrothermal alteration. The volcanic complexes and related intrusions are preserved in fault-bounded cauldron-subsidence areas, e.g. Newcastle Range Volcanics. Dyke swarms, breccia pipes and hydrothermal alteration systems are commonly associated with cauldron subsidence. Some sequences are underlain by coarse, terrestrial, clastic sediments.

Uranium mineralisation occurred during two main episodes of volcanic activity and co-magmatic intrusion (Fig. 41) — Late Devonian to Early Carboniferous, and Late Carboniferous to Early Permian. The volcanics are predominantly continental welded ignimbrites of rhyolitic composition. These ignimbrite sequences are generally associated with concentric (ring) or linear fracture–intrusion systems that define single or composite cauldron subsidence structures. Extrusive rocks of the Newcastle Range and Featherbed volcanics and intrusive equivalents are variably fractionated I-type volcanics. The Early Permian episode produced mostly intermediate and basic volcanics. They overlie Lower Carboniferous clastic sedimentary rocks or older basement.

The granitoid intrusions are mostly small and commonly oval or circular in cross-section, with narrow thermal metamorphic aureoles. They comprise medium to coarse biotite granite, adamellite and granodiorite. Many are subvolcanic and grade through porphyritic microgranite into comagmatic acid volcanics.

The uranium–fluorine–molybdenum deposits in the province are spatially and genetically related to the acid volcanics. Bain (1977) considered that this type of mineralisation is hydrothermal and the deposits accumulated in zones of high porosity and permeability, at shallow depth below the volcanic land surface and accessible to mineralising hydrothermal fluids. Intensely jointed rock, breccia pipes, fault zones, unconformities and permeable clastic strata act as hosts for mineralisation.

Ben Lomond deposit

The Ben Lomond deposit is 60 km west-south-west of Townsville (Fig. 41). Having discovered the deposit in 1976, Minatome Australia Pty Ltd completed a major drilling program to delineate it and also to test other radiometric anomalies on and around the Ben Lomond Ridge.

Delineation of the eastern portion of the orebody by surface drilling was difficult and expensive because of the thick sequence of barren rhyolites (Watershed North Rhyolite) overlying the orebody (Fig. 42). These volcanics increase in thickness to the east. From 1979 to 1981, an adit was driven for approximately 300 m along the mineralised zone, several cross-cuts were developed through the zone, and a program of underground drilling to test the orebody was completed. During development of the cross-cuts, approximately 3500 t ore averaging 0.21% U_3O_8 was mined and this ore was stockpiled on the lease (Afmeco, 1996). Exploration drilling carried out along the Ben Lomond Ridge to the east indicated that the mineralised structure and host rock extend well beyond the delineated deposit.

Mining leases covering the mineralisation were granted to Minatome in 1980 and 1983. A draft EIS for the project was released in 1983, and after comments from Government and the public the final EIS was released in 1984. The project was not developed because the Commonwealth Government introduced the ‘Three mines’ policy in 1983.

Geology

The Ben Lomond deposit (Fig. 42) is in rhyolitic tuff of the early Carboniferous St James Volcanics (Glenrock Group) (Valsardieu & others, 1980). Basement rocks are the Neoproterozoic Argentine Metamorphics, comprising schist, amphibolite, quartzite and granitic masses (Wyatt & others, 1970). Sandstone, siltstone and mudstone of the Keelbottom Group (Late Devonian–Early Carboniferous), unconformably overlie the basement and are in turn overlain by the St James Volcanics. The St James Volcanics consist of rhyolitic tuff with subordinate andesitic volcanics and clastics. From the regional structure and distribution of faulting it appears that these volcanics accumulated in a cauldron-collapse structure (Valsardieu & others, 1980) and were deformed during cauldron subsidence.

The St James Volcanics are unconformably overlain by rhyolitic ignimbrites of the Watershed North Rhyolite (Hutton & others, 1997). Conglomerate, sandstone and siltstone of the late Carboniferous Insolvency Gully Formation, which outcrop 200 m north of the orebody, unconformably overlie the Watershed North Rhyolite.

The uranium–molybdenum mineralisation is in a complex system of subparallel, steeply-dipping veins and fractures associated with a wide shear zone (Fig. 42). The upper limit of the mineralised vein system is a few metres below the unconformity at the base of the Watershed North Rhyolite. The fracture system does not extend into the overlying Watershed North Rhyolite. Mineralisation is best developed 10–50 m

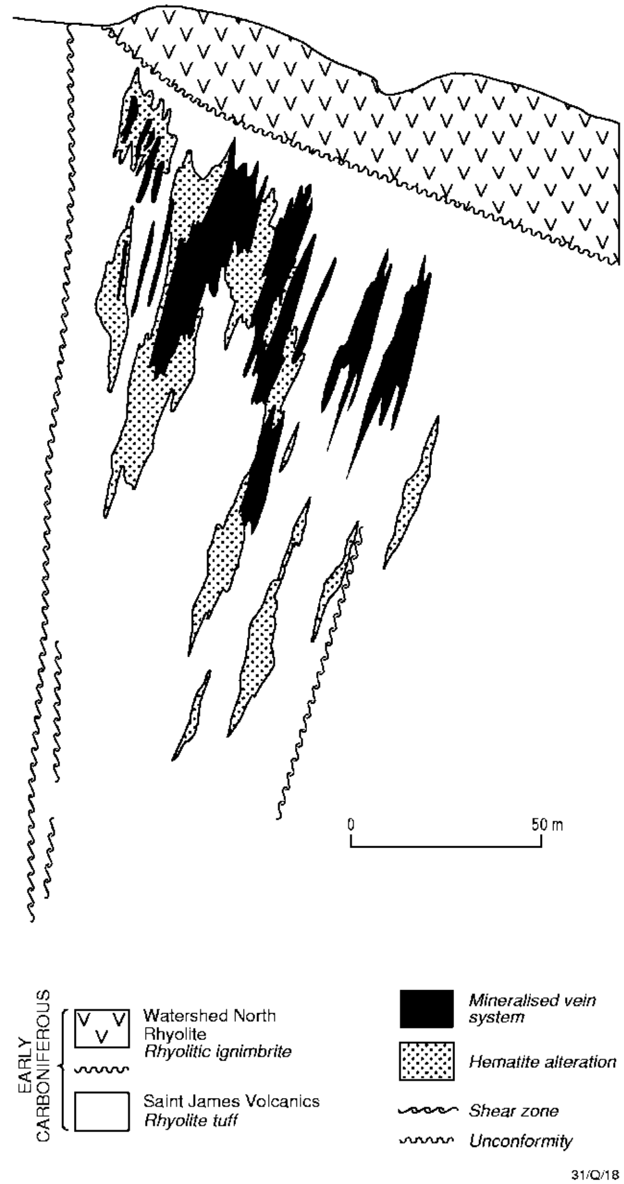

Figure 42. Cross-section, Ben Lomond deposit (after Minatome Australia Pty Ltd, 1983)

below the unconformity. The vein system is mineralised over a length of more than 750 m, a maximum width of 150 m and vertical depth of 100 m. The mineralised zone is parallel to the axial plane of a shallow plunging syncline in the host rhyolitic tuff.

The primary mineralogy includes pitchblende, coffinite and molybdenite, with minor amounts of uranium phosphate (torbernite and metatorbernite) and jordisite (amorphous MoS_2). Minor amounts of galena, sphalerite and arsenopyrite also occur in the ore. The mineralised veins are closely associated with silicic and hematitic alteration which causes the host rocks next to the veins to be brownish-red.

Resources

The measured and indicated mineral resources were estimated to total 6792 t U_3O_8 with an average grade of 0.228% U_3O_8, and 4578 t Mo with an average grade of 0.149% Mo. This estimate was for the 750 m strike length of mineralisation which had been tested by drilling along 25 m spaced sections (Afmeco, 1996).

Minatome proposed to mine the western part of the deposit by open cut. An underground mine was proposed for the eastern part which is covered by a high ridge of Watershed North Rhyolite. Mineable reserves in both the proposed open cut and underground mine were estimated as 1 930 000 t ore averaging 0.246% U_3O_8 (0.209% U) and 0.159% Mo. This represents 4758 t U_3O_8 (4035 t U) and 3026 t Mo (Minatome Australia Pty Ltd, 1983). The estimate includes losses due to mining and also losses due to upgrading by radiometric discriminators. The cut-off grades used were 0.12% U_3O_8 (0.1% U) for the open pit, and 0.16% U_3O_8 (0.135% U) for the underground operation.

Maureen deposit

The Maureen deposit is 35 km north-west of Georgetown (Fig. 41). Uranium–fluorine–molybdenum mineralisation forms irregular stratabound zones in a sequence of conglomerate, sandstone, siltstone and overlying volcanics (Fig. 43). These host rocks are part of the Late Carboniferous to Early Permian Maureen Volcanic Group, a sequence of rhyolitic ignimbrite and agglomerate with subordinate basalt and clastic strata (Withnall & others, 1997). The clastics are markedly thicker (320–400 m) in the vicinity of the deposit, which occurs in the lowermost 60 m of these sediments. The Maureen Volcanics accumulated in a cauldron subsidence structure. The sequence directly overlies Etheridge Group metamorphics (Palaeoproterozoic) on the north-western edge of the Georgetown Inlier.

Mineralisation has filled fractures and replaced the matrix, some clasts and, locally, the entire rock. It is commonly associated with hematitic alteration and bleached wallrock. Hydrothermal solutions ascending along major faults and fracture systems precipitated mineralisation in the porous and permeable clastics at the base of the volcanic sequence (O'Rourke, 1975).

The primary mineralogy is uraninite, purple fluorite and fine-grained complex molybdenum minerals. The molybdenum (including uranium–molybdenum) minerals include molybdenite, ferrimolybdite, umohoite, wolfenite, powellite, ilsemannite and iriginite (Bain, 1977). In the oxidised zone, the uranium minerals are mainly complex uranium phosphates, including saleeite, renardite, meta-uranocircite, autunite and meta-autunite. Gangue minerals are mainly barite, gypsum, kaolinite and hematite.

The estimated in situ resources for the Maureen deposit (Central Coast Exploration NL, 1979) are shown in Table 26, based on a cut-off grade of 0.035% U_3O_8. Molybdenum resources were not reported.

Table 26. Estimated in situ resources, Maureen deposit, as in company reports

	Ore (t)	Grade (% U_3O_8)	U_3O_8 (t)
Proved	1 650 330	0.153	2 528
Probable	732 670	0.056	412
Total	2 383 000	0.123	2 940

Other deposits

There are many small deposits and prospects in the Georgetown region, particularly along the western edge of the Newcastle Range Volcanics (Fig. 41). From 1972 to 1983, Minatome Australia Pty Ltd carried out a major exploration program over the Newcastle Range Volcanics using helicopter and fixed wing airborne surveys, geological mapping, ground geophysics and drilling. It found that uranium mineralisation occurs in two geological settings (Withnall & others, 1997):

- *stratabound mineralisation* in coarse fluviatile sediments of the Devonian to Carboniferous Gilberton Formation that underlie the various Carboniferous to Permian volcanic groups throughout the region; examples include the Maureen deposit and the Turtle Arm, Dagworth, Chinaman Creek and Mount Tabletop prospects;

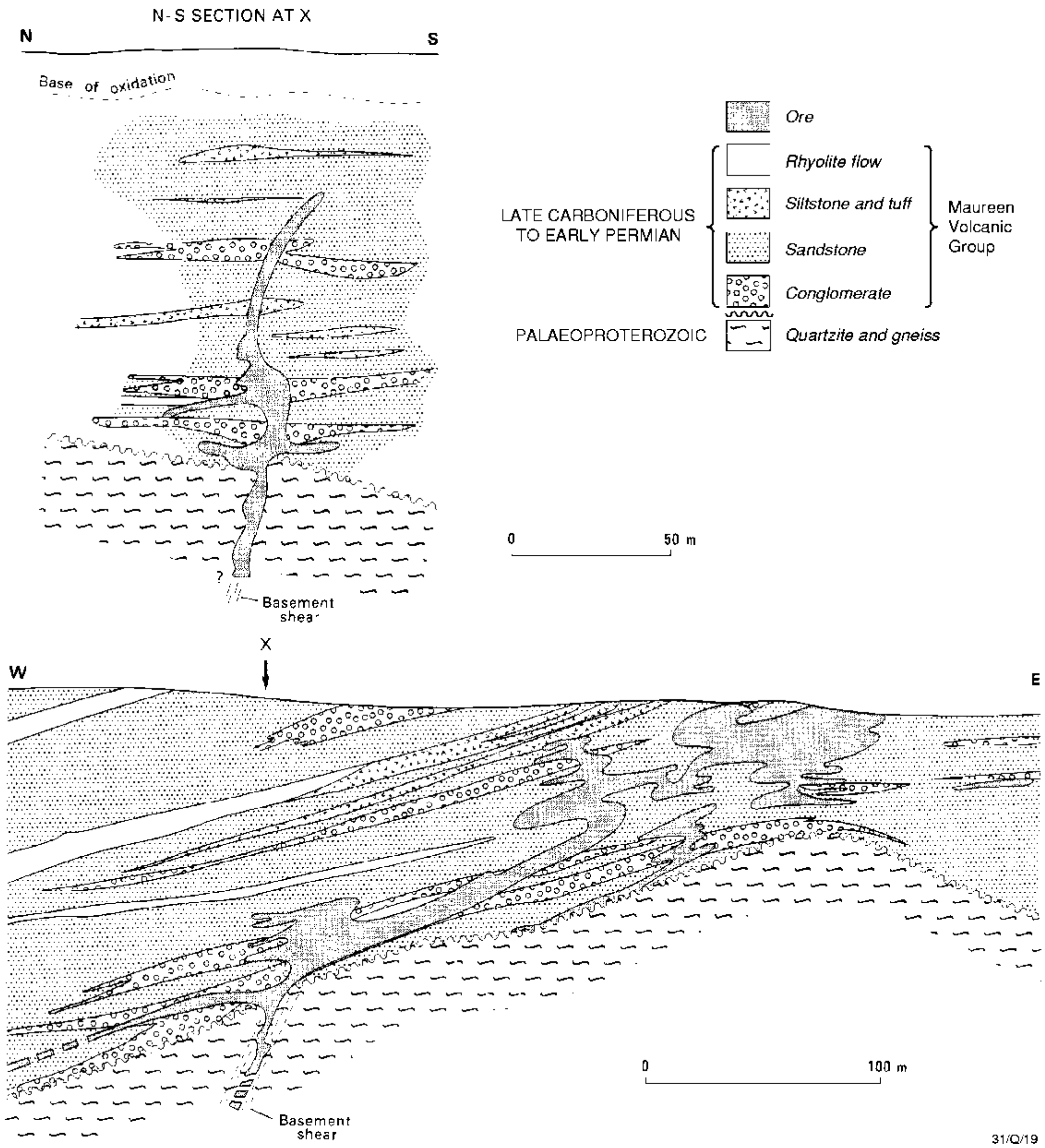

Figure 43. Cross-section and long-section of the Maureen deposit (after Bain & Withnall, 1980)

- *fault and fracture-controlled mineralisation* associated with Carboniferous to Permian volcanic subsidence structures and felsic porphyry dykes. Some of these deposits are in Proterozoic metasediments adjacent to the contact with the volcanics. In the metasediments, the mineralisation is closely associated with Carboniferous porphyritic acid, intermediate and basic dykes (Crane, 1983). Examples include the prospects Laura Jean, the Lineament Group, the Fiery Creek group (Twogee, Trident, Four Geo, Phillips Well), Limkins and Mount Hogan.

Mineralisation and host rocks at **Turtle Arm** prospect (Fig. 41), 5 km north-east of Maureen deposit, are similar to Maureen.

Dagworth prospect is in extensively brecciated clastics and andesite at the base of the Newcastle Range Volcanics. Mineralisation is related to fault zones.

Chinaman Creek prospect, in pyritic sandstone at the base of the Late Devonian Gilberton Formation (Osborne, 1978), appears to be controlled by sedimentary features rather than by faulting.

At the **Fiery Creek** prospects, basal quartzofeldspathic sandstone, arkose, conglomerate and minor siltstone of the Newcastle Range Volcanics have been intruded by rhyolitic dykes. The area has been extensively faulted. Mineralisation has accumulated in zones of fracturing and brecciation in a variety of host rocks, including Proterozoic metasediments, rhyolitic dykes, arkosic clastics, ignimbrite and andesite. At Twogee, total resources outlined by drilling amount to 755 t U_3O_8, averaging 0.12% eU_3O_8 (Crane, 1983).

Trident prospect is in Proterozoic basement rocks, 1 km west of their contact with the Newcastle Range Volcanics. Mineralisation occurs along the brecciated footwall of a dolerite dyke. In situ resources amount to 495 t U_3O_8 averaging 0.22% eU_3O_8 (Crane, 1983).

At **Phillips Well** prospect, a complex system of Carboniferous rhyolite, andesite and microgranite dykes intrudes migmatite and granite.

Laura Jean prospect (25 km east of Georgetown) is in brecciated dacite in a fault zone along the eastern edge of the Newcastle Range Volcanics (Bain, 1977). It is cut by dykes of porphyritic microgranite and veins of purple fluorite.

The **Lineament Group** of uranium–gold prospects occupies zones of intense alteration along the Drummer Hill Fault (Bain & Withnall, 1984). The main prospects are the Central 50, West 30, West 24, Somerset and East 72. Rhyolite and dolerite dykes, intruded along the fault zone, have also been intensely altered.

At **Limkins** prospect (52 km south-south-east of Forsayth), mineralisation is in a 1 m wide fractured quartz vein, next to hydrothermally altered granodiorite (Wyatt, 1957). Metatorbernite, autunite, pyrite and traces of galena occur in veinlets and fractures.

The **Mount Hogan** prospect, 68 km south-south-east of Forsayth, consists of gold–silver–uranium mineralisation in a system of narrow quartz veins in altered Proterozoic biotite granite. The veins are thin (0.2–0.6 cm), but the enclosing alteration zones extend up to 15 m away from the veins (O'Rourke & Bennell, 1977). Native gold, tetrahedrite, torbernite, metatorbernite, pitchblende, phosphuranylite, molybdenite and fluorite occur in both the quartz veins and the altered granite. Bain and Withnall (1980) suggested that the hydrothermal fluids and mineralisation were introduced into the fracture from a nearby rhyolite stock of late Palaeozoic age.

The **Oasis** prospect (50 km south-east of Einasleigh) was discovered by Australian Anglo American Ltd in 1973 and was originally called the Lynd Prospect (Hoyle, 1974). Staff of Central Coast Exploration NL renamed the prospect when they drilled it in 1978–79 (Central Coast Exploration NL, 1979). The mineralisation is in a small roof pendant of quartz–biotite–chlorite schist in Proterozoic porphyritic granite, and extends over a length of 200 m. The primary mineralogy is fine-grained uraninite within biotite and chlorite. The secondary uranium (phosphate) minerals include autunite, meta-autunite, torbernite, sabugalite and bassetite.

The **Werrington Group** comprises minor uranium occurrences associated with fault zones in the Proterozoic graphitic Juntala Schist (Tucker, 1978).

Secondary uranium minerals are present in old copper–silver workings at the **Kaiser Bill** prospect (12 km west of Einasleigh) and **Quest-End** prospect (35 km east of Georgetown).

In the Herberton–Mount Garnet area, many of the wolframite–cassiterite lodes contain secondary uranium minerals. At the **Treasure** mine, 15 km north-north-west of Mount Garnet, torbernite, minor molybdenite and fluorite accompany cassiterite and wolframite in greisen in the Elizabeth Creek Granite (Blake, 1972). In the **Stannary Hills** area, 18 km north-west of Herberton, torbernite, metatorbernite and fluorite occur in a hydrothermally altered fault zone separating sandstone (Hodgkinson Formation) and porphyritic rhyolite from Elizabeth Creek Granite (Bain, 1977).

INTRUSIVE DEPOSITS

Intrusive deposits of uranium are found at the Olary uranium field (SA) and the Gascoyne Complex (WA), and small prospects are known in the Strangways Range (NT).

OLARY URANIUM FIELD

Until 1944 the only two significant occurrences of uranium mineralisation known in Australia were at Radium Hill and Mount Painter (SA) (Fig. 26). Radium Hill, in the Olary field, 340 km north-east of Adelaide, was discovered in 1906. In 1910 uranium-bearing minerals were also found at Radium Ridge in the Mount Painter field, 300 km to the north-west. Radium was mined intermittently from the Radium Hill deposit and Mount Painter field until 1934, when both were forced to close down owing to the complex mineralogy of the ores and the discovery of pitchblende at Great Bear Lake in Canada (Campana & King, 1958; AAEC, 1962).

In 1944–45 Commonwealth and South Australian Government personnel examined Radium Hill for uranium potential but found the deposit to be low-grade and too small to be of immediate importance. The South Australian Government resumed investigations in 1945, and by 1950 it was concluded that potential resources at Radium Hill would justify mining and treatment of the deposit. In 1952, the Commonwealth and South Australian Governments and the Combined Development Agency wrote a contract that enabled the Radium Hill deposits to be worked. The mineralogy of the ore was complex. A beneficiation plant was built at the mine site and a hot acid-leach chemical treatment plant was built at Port Pirie. The mine was operated by the South Australian Department of Mines from 1954 to 1961. In 1968 the Port Pirie plant was sold to Rare Earth Corporation of Australia Ltd for the processing of rare earths derived from the beach-sand industry in other States (Ingram, 1974).

In 1951 a reconnaissance aerial radiometric and ground survey conducted by the South Australian Department of Mines located a uranium deposit near Crocker Well. In 1953, technical staff and prospectors of the South Australian Department of Mines began regional mapping and prospecting in the Olary field. As a result, additional radioactive prospects were located in the Crocker Well and Mount Victoria areas.

Both the Olary and Mount Painter fields were extensively explored for uranium from 1968 to 1982 and the details of this exploration are given in Yates (1992). Esso Exploration and Production Incorporated was the most aggressive uranium exploration company, drilling 25 000 m in 1977–78 in its search for a bulk mineable low-grade deposit. Most of this drilling was in the Crocker Well area.

To revitalise exploration for all minerals in the Willyama Inliers in South Australia and New South Wales, Mines and Energy South Australia (MESA), New South Wales Department of Mineral Resources and Geoscience Australia are collaborating in a major program of new data acquisition and interpretation over the Olary and Broken Hill regions. This program is referred to as the Broken Hill Exploration Initiative. Major components of the program in South Australia include high-resolution airborne magnetic and radiometric surveys, gravity surveys, detailed geological mapping and interpretation.

Regional geological setting

Radium Hill, **Crocker Well** and **Mount Victoria** uranium deposits are in Mesoproterozoic granitoids of the Willyama Inlier in the Olary region of South Australia.

Late Palaeoproterozoic metasedimentary and metavolcanic rocks of the Willyama Supergroup form a series of inliers in eastern South Australia and western New South Wales. In South Australia these rocks are referred to as the Olary Domain. The Willyama Supergroup stratigraphy in the Olary Domain has been described by Callen (1990), Forbes (1991), Flint and Parker (1993), Ashley and others (1995) and Robertson and others (1998). The metasedimentary and meta-igneous succession, starting from the base, is:

- *composite gneiss suite*, consisting of migmatitic gneisses and granitoids. The main rock type is coarse-grained and migmatitic quartz–feldspar–biotite ± sillimanite ± garnet gneiss. Stratiform quartz–biotite–magnetite gneiss, mafic gneisses, sillimanite-garnet schists and quartzite are also present. Coarse-grained microcline-rich granitoids and pegmatites also occur.
- *quartzofeldspathic suite*, consisting of massive to well-layered quartz–albite–biotite–K-feldspar–gneiss. This suite is considered to be metasedimentary in origin because the gneisses contain metamorphosed sedimentary structures. Psammopelitic and pelitic schists form part of this sequence in some areas.

Ashley and others (1995) proposed that the quartzofeldspathic suite rocks were extensively altered by saline-rich fluids, at various times, from early diagenesis to high-grade metamorphism. Albitisation is the most common alteration process in this modification.

The other metasedimentary sequences within the Willyama Supergroup are the *Calc-silicate suite* (calc-silicate, calc-albite and feldspathic rocks), *Bimba formation* (a thin sequence of albitic metasiltstones, marble and calc-silicate rocks) and *Pelite suite* (graphitic quartz–mica–andalusite–sillimanite schist).

The Willyama metasedimentary and meta-igneous rocks in the Olary Domain have been complexly deformed and metamorphosed. Several deformation phases occurred during the peak metamorphism of the Olarian Orogeny which reached amphibolite facies. This orogenic event has been dated at 1600 ± 8 Ma in Willyama metamorphics at Broken Hill (Page & Laing, 1992). Further folding and deformation of the Willyama metamorphics also took place during the Palaeozoic Delamerian Orogeny.

Granitoid intrusions are widespread in the Olary Domain. The most voluminous intrusives are those of the syn- to post-tectonic 'regional granitoids' — leucocratic, foliated biotite monzogranites, which form large dome-shaped outcrops. They are S-type granitoids which commonly contain biotite and muscovite. The ages for these granitoids include 1579 ± 2 Ma from a sodic granitoid at Crocker Well (Ludwig & Cooper, 1984) and approximately 1590 Ma from a granite at Triangle Hill (Cook, Fanning & Ashley, 1994). The 'regional granitoids' appear to be contemporaneous with Olarian high-grade regional metamorphism and deformation, and with the major Hiltaba Suite–Gawler Range Volcanic magmatic event at approximately 1595–1585 Ma (Flint, 1993) and associated Olympic Dam-style mineralisation on the Gawler Craton (Cross & others, 1993).

Pegmatites are widespread in the Olary Domain and they form both concordant and discordant bodies. Most appear to be related to the 'regional granitoid' magmatic event (Robertson & others, 1998). These pegmatites are composed of albite–quartz–muscovite and microcline–quartz–albite–muscovite.

The Willyama metamorphics are unconformably overlain by Neoproterozoic (Adelaidean) and Cambrian sediments (sandstone, siltstone and carbonates) of the Adelaide Geosyncline.

Thorian brannerite, as at Crocker Well, is consistently associated with sodic granite, and many of the pegmatites contain uranium, thorium and rare earth element minerals. At Mount Victoria, granite and migmatite contain pods of biotite–scapolite–quartz schist containing abundant rutile, davidite, zircon, monazite and xenotime. At Radium Hill, davidite ore occurs in pegmatite veins, along shears and in fractures within host rocks comprising gneiss and amphibolite of the Willyama Supergroup (Whittle, 1954; Blisset, 1975; Ashley, 1984; Ludwig & Cooper, 1984). The pegmatite veins occur along shear zones.

Ashley (1984) proposed that the sodic granite was derived from anatexis of the sodic felsic gneiss during high-grade metamorphism. The bulk of the thorian brannerite was deposited contemporaneously with a fluorine-rich assemblage from saline fluids evolved during crystallisation of the granite; mineralisation took place in fractures and breccias as the granite cooled. The less abundant disseminated thorian brannerite probably crystallised directly from the sodic granitic melt.

Age dating work by Ludwig and Cooper (1984) on U–Pb–Th data from Crocker Well, Mount Victoria and Radium Hill yielded very scattered and discordant apparent ages, but the results obtained are consistent with primary ages of about 1580 Ma for Crocker Well and even older for Radium Hill and Mount Victoria.

Radium Hill deposit

The Radium Hill deposit was mined intermittently for radium from 1906 to 1931, yielding a total of 350 mg radium bromide from 97 t concentrate. Between 1954 and 1961, when mined for its uranium content, the deposit produced 969 300 t davidite ore, grading 0.11–0.15% U_3O_8. Beneficiation yielded about 152 000 t concentrate which was treated at Port Pirie; and 852 t U_3O_8 was sold (Parkin, 1965; Major, 1984). The Radium Hill concentrate contained appreciable amounts of rare earth oxides (lanthanum, cerium, yttrium and scandium). During the later years of mining, scandium was recovered as a by-product of uranium treatment.

The deposit was worked underground to a depth of 290 m and the shaft reached a depth of 335 m. Most of the production came from the Mine Lode System. The lodes had a strike length of 1400 m and varied greatly in width, averaging about 1 m but locally reaching 7.5 m wide (Blisset, 1975). Mineralisation was intersected in drill holes to a depth of 450 m.

Uranium–rare earth element mineralisation occurred in narrow, steeply dipping pegmatitic veins in sericitic shear zones within high-grade quartzo–feldspathic gneiss and amphibolite. The pegmatite consisted of quartz–biotite–ilmenite–K feldspar. Whittle (1954) referred to these as ‘aplite dykes’.

The host rocks are paragneiss and amphibolite of the Willyama Supergroup, folded into a dome-like structure. The orebodies occupied north-east-striking, steeply dipping, subparallel shear zones cutting dragfolds on the overturned western limb of the dome. The main ore mineral was davidite, intergrown with hematite, ilmenite and rutile, and the main gangue was biotite and quartz. Small amounts of pyrite, chalcopyrite and arsenopyrite were present in all lodes. Within 30 m of the surface, carnotite was the main secondary uranium mineral.

Esso Exploration and Development Incorporated re-evaluated the Radium Hill deposit in 1981 and reported that the resources, largely below previous mining which extended as deep as 290 m, were insufficient to warrant further consideration (Yates, 1992). The remaining mineral resources below the old mine workings were estimated to be 890 000 t averaging 0.009% U_3O_8 (Robertson & others, 1998).

Mount Victoria deposit

The **Mount Victoria** deposit (Campana & King, 1958), 90 km west-north-west of Radium Hill, was discovered in 1954. It has been tested by drilling and underground exploration. Uranium mineralisation is localised along a system of south-dipping fracture zones in foliated migmatitic granite and gneiss. The mineralisation consists of ‘disseminated daviditic iron–titanium minerals in a matrix of medium-grained biotite, albitic feldspar and apatite’. Impure davidite, rutile and hematite occur as composite granules and irregular segregations replacing or partly replacing the biotitic matrix. Campana & King (1958) estimated the probable reserves as 69 000 t ore at 0.31% U_3O_8 and possible resources as 41 000 t ore at 0.22%

U_3O_8. More recently North Flinders Mines Ltd (1979) stated that mineable reserves were conservatively estimated at 66 000 t ore with production grades of about 0.3% U_3O_8.

Crocker Well deposit

The **Crocker Well** deposit (King, 1954; Campana & King, 1958; Ashley, 1984), about 10 km south of Mount Victoria, was detected by an airborne reconnaissance survey in 1951. Ashley (1984) stated that a resource of at least 10 Mt of mineralisation averaging 500 ppm U_3O_8 to a depth of 100 m had been outlined. Thorian brannerite mineralisation at the Crocker Well deposit occurs in 'regional granitoids' including sodic granite, trondhjemite and sodic alaskite and associated sodic felsic gneiss. There are several zones of mainly fracture-controlled and disseminated mineralisation in an area of about 4 km^2. Significant uranium–thorium mineralisation is restricted to fractures and local phlogopite-rich breccias. The breccias form diatreme-like bodies and dykes, ranging from less than 1 cm to 40 m across, which contain angular inclusions of adjacent granitic rock and gneiss in a phlogopite-rich matrix. The higher-grade uranium–thorium mineralisation is accompanied by higher fluorine values (Ashley, 1984).

The alaskites and trondhjemites that host the mineralisation are considered to have formed by metamorphism and anatexis of compositionally similar nearby sodic felsic gneisses (albitites) (Ashley, 1984).

Other deposits

At **Crocker Well East**, thorian brannerite accompanies davidite, which is present either as discrete grains or intergrown with the brannerite.

At the **Jagged Rocks** prospect, small discontinuous segregations of davidite occur in biotite migmatite (Robertson & others, 1998).

The **Spring Hill** occurrence (Campana & King, 1958) was discovered by a prospector in 1953. Davidite mineralisation is localised in highly fractured hybrid granite and granitised sedimentary rocks. The ore mineral is daviditic ilmenite, superficially stained with (?)carnotite, which forms coarse-grained aggregates associated with biotite.

Davidite and thorian brannerite are also known in rocks of the Willyama Complex in western New South Wales, at **Thackaringa** (Rayner, 1960).

GASCOYNE COMPLEX

In the Gascoyne Complex (WA) (Fig. 23), uraninite-bearing pegmatites occur in the Palaeoproterozoic Morrissey Metamorphic Suite, which is widely migmatised. Intrusive pegmatite and alaskite form extensive belts throughout the Morrissey Metamorphics and the alaskite closely resembles the host rocks at the Rossing uranium deposit in Namibia (Carter, 1982).

Agip Nucleare Australia Pty Ltd discovered uranium in pegmatite, 3 km north of **Mortimer Hills** in 1974. Mineralisation was initially detected by an airborne survey. From 1974 to 1978, Agip mapped the prospect in detail, did a ground radiometric survey and drilled 33 non-core holes (Carter, 1982).

The Mortimer Hills pegmatite is in the Yinnietharra pegmatite belt that extends for about 20 km. The main body measures 1000 m long and up to 400 m wide. The mineralisation is uraninite, uranophane and beta-uranophane. Agip's drilling intersected only low-grade mineralisation, the best intersection being 150 ppm U (0.015%) over 1 m (Carter, 1982).

In 1998, Acclaim Uranium NL was granted exploration tenements over several areas covering uranium occurrences in pegmatites to the south of Mortimer Hills. The company re-evaluated the existing drill hole data and carried out limited exploration in the area for uranium in pegmatites and also in calcretes (Acclaim Uranium, 1998).

CENTRAL AUSTRALIA

The **Mordor Igneous Complex** in the Strangways Range, 65 km north-east of Alice Springs, contains basic intrusives (with kimberlitic affinities) and potassium-rich intrusives (Shaw & Langworthy, 1984). Small zones of uranium and thorium silicate mineralisation occur in syenitic intrusives.

Uranium and rare earth minerals have been recorded in pegmatites associated with adamellite in the Granite Downs area, eastern Musgrave Block, about 360 km south southwest of Alice Springs (Coats, 1963).

VEIN DEPOSITS

In Australia, there are many small vein deposits of uranium and these are widely distributed in Proterozoic and Phanerozoic host rocks including: Gascoyne and Lamboo Complexes (WA), Lincoln and Barossa Complexes, Denison Block and Peak Metamorphics (SA), Lachlan and New England Fold Belts (NSW, Victoria & Tasmania) .

Small base-metal vein deposits containing some uranium at **Mundong Well** (Fig. 23) in the Gascoyne Complex occur as small shoots formed on slight bends in faults cutting migmatite, gneiss and schist of the Palaeoproterozoic Wyloo Group (Blockley, 1975). The principal uranium mineral is kasolite, which is associated with cerussite, galena, sphalerite, malachite, chrysocolla, fluorite, calcite and magnetite. The veins are close to a major regional unconformity, where the Wyloo Group is overlain by Mesoproterozoic sandstone of the Bangemall Basin. The discovery of this occurrence in the early 1970s led to a sudden increase in uranium exploration in the Gascoyne Complex because the geological setting was considered similar to that of the Alligator Rivers uranium field (see the chapter on 'Unconformity-related Deposits').

Six small uranium prospects occur near Port Lincoln (SA) (Fig. 31) in quartz–feldspar–hornblende gneiss and amphibolite of the Palaeoproterozoic **Lincoln Complex** (Johns, 1961). Pitchblende forms disseminations, fracture coatings and veins.

In the Mount Lofty Ranges (SA) east and north-east of Adelaide, uranium mineralisation occurs in inliers of the Palaeoproterozoic Barossa Complex near **Houghton**, and also about 61 km south of Adelaide, at **Myponga** (Dickinson & others, 1954; Parkin, 1957; Ingram, 1974).

South Australian Government agencies investigated the Myponga prospect in the mid-1950s and about 346 t ore was treated at Port Pirie to yield 0.8 t U (0.99 t U_3O_8) in 1957–58 (Australian Atomic Energy Commission file data). The mineralisation was considered to be too erratic for development.

Several occurrences have been recorded in the Palaeoproterozoic Denison Block (SA): uranium and copper at the Last Chance mine and uranium in the Peake Metamorphics, 6 km south-west of Mount Kingston (Blissett, 1975).

In the Lachlan and New England Fold Belts in New South Wales (chiefly early and late Palaeozoic respectively), uranium occurs in polymetallic veins and shear zones either within or along the margins of some post-tectonic granites. These veins also contain copper, lead, tin, tungsten and molybdenum mineralisation. None of the deposits has been worked for uranium. The three main prospects are Blackfellows Dam, Carcoar and the Whipstick mine (Rayner, 1960). At **Blackfellows Dam**, near Nymagee, uranium occurs in a copper–lead–zinc–silver vein in granite. At **Carcoar**, 40 km south of Orange, uranium accompanies cobalt, molybdenum and copper mineralisation in a vein in early Palaeozoic slate and andesite; and at the **Whipstick** mine, 24 km west of Pambula, uraninite and torbernite occur in a molybdenum–bismuth ore-pipe in granite. Further north, uranium mineralisation occurs in tin–tungsten lodes associated with Permian granites at Torrington, Emmaville, The Gulf, Gilgai, Watson's Creek and Gordonbrook (Ingram, 1974).

In the Lachlan Fold Belt in Victoria, several occurrences have been reported. At **Mount Kooyoora** (Spencer-Jones & Bell, 1955), 50 km north-west of Bendigo, secondary uranium mineralisation has been found in superficial ironstone overlying granite. Secondary mineralisation in veins and fractures in granite has been recorded at **Lake Boga**, 20 km south of Swan Hill, at **Wycheproof**, 80 km south-south-west of Swan Hill, and in gold-bearing veins at the **Sunnyside Goldfield**, 50 km north of Omeo (Ingram, 1974).

Several occurrences are known in the Lachlan Fold Belt in Tasmania. At the **Royal George** tin mine, 16 km east of Avoca, uranium occurs in tin-bearing greisen (Hughes, 1956). Minor mineralisation in veins and fractures within granite has been recorded at **Chwalczyk's** prospect in the Storeys Creek area (Blissett, 1959), at the Anchor tin mine 95 km north-north-east of Launceston, and in the Heemskirk district 16 km west of Zeehan (Hughes, 1957).

A number of vein-like uranium deposits occur in the Pine Creek Inlier. They are considered to have formed by geological processes similar to those that produced unconformity-related deposits. These vein-like deposits are described in the chapter called 'Unconformity-related Deposits' under the heading 'Vein-like uranium deposits in the Pine Creek Inlier'.

The **Pandanus Creek**, **Cobar 2**, **El Hussen** and 'vertical-type' mineralisation in the Westmoreland–Pandanus Creek uranium field are also vein-type deposits, but have been described already, with the larger deposits hosted in sandstone.

About 12 uranium occurrences are located about 210 km north-north-east of Halls Creek in the Western zone of the Lamboo Complex in the Halls Creek Orogen (WA). These occurrences have been summarised by Hassan (2000) and classified as 'vein and hydrothermal — undivided'. The occurrences include the **Frog** prospects, where secondary uranium mineralisation occurs in the Whitewater Volcanics (~1855 Ma SHRIMP U–Pb; Griffin & others, 2000) in fractures, joints and breccia zones with fluorite. At **Dunham River B**, torbernite occurs in a brecciated dolerite dyke along the Dunham Fault zone and in mineralised quartz veins in sheared Crooked Creek Granite adjacent to the dyke. At **Donkey Creek**, secondary uranium mineralisation occurs in siltstone of the Golden Gate Siltstone of the Carr Boyd Basin in the Dunham Fault Zone (Fraser, 1955; Dale, 1976 in Hassan, 2000).

About 65 km north of Halls Creek, at the **Antares** prospect, secondary uranium mineralisation occurs in fractures and joints in felsic tuff of the Whitewater Volcanics; several mineralised zones are up 20 m long and 10 m wide.

Uranium mineralisation is also present in the Red Rock Formation of the Red Rock Basin at **John Galt**, about 130 km north-north-east of Halls Creek (Hassan, 2000). Carnotite occurs in boulders of silicified sandstone, and autunite and torbernite are present on cleavage planes of mylonitic breccia boulders. Uranium is also present in xenotime-bearing veins at other nearby prospects, **John Galt (REE 1)** and **John Galt (REE 2)**.

QUARTZ-PEBBLE CONGLOMERATE DEPOSITS

Quartz-pebble conglomerates containing uranium (and gold) are known to occur in four tectonic units in Western Australia: Hamersley Basin, Yerrida Basin (previously referred to as Nabberu Basin), Halls Creek Orogen and the Pilbara Craton (Fig. 23). There has been a considerable amount of exploration and drilling for palaeoplacer deposits of uranium and gold in these conglomerates, particularly in the Hamersley Basin. However, to date, no uranium or gold concentrations of commercial significance have been identified.

Low-grade thorium–uranium mineralisation occurs at several places in quartz-pebble conglomerate in the basal sediments of the Kimberley Basin, but these conglomerates are much younger than typical uranium-bearing quartz-pebble conglomerates.

HAMERSLEY BASIN

Low-grade uranium mineralisation has been intersected in Archaean quartz-pebble conglomerates in the lower Fortescue Group, the lowermost unit in the Hamersley Basin. The Fortescue Group unconformably overlies Archaean granitoids, greenstones and sediments of the Pilbara Block (Carter, 1981; Hickman, 1983; Hickman & Harrison, 1986). Within the lower Fortescue Group, uranium-bearing quartz-pebble conglomerates occur in the Hardey Sandstone and in an unnamed conglomerate–sandstone sequence above the Kylena Basalt which overlies the Hardey Sandstone (Carter & Gee, 1988). Both the Hardey Sandstone and the younger unnamed conglomerate–sandstone sequence were deposited within intermontane basins lying along Archaean greenstone lowlands.

Exploration and drilling of these conglomerates has been concentrated in three areas — the Nullagine Sub-basin which lies immediately west of Nullagine; the Marble Bar Sub-basin which lies immediately west of Marble Bar; and the West Pilbara Sub-basin which lies in the general area 150 km south-west of Port Hedland (Hickman & Harrison, 1986; Carter & Gee, 1988).

The results from a number of drilling programs in these conglomerates are summarised in Carter and Gee (1988). No economic deposits of uranium (or gold) have been identified, but a number of encouraging drill intersections have been made.

In the Nullagine Sub-basin, drilling by Cominco Exploration Pty Ltd intersected 0.6 m averaging 425 ppm U_3O_8 (0.0425%) in conglomerate of the Hardey Sandstone at **Bonnie Creek**, 30 km south-west of Nullagine (Fig. 23). The highest values are in conglomerate that contains pyrite as poorly rounded detrital grains and large irregular masses in the matrix. In the mineralised areas, the conglomerate contains mostly quartz pebbles, whereas the unmineralised parts contain a large proportion of rock fragments.

In the Marble Bar Sub-basin, a drill intersection of 0.3 m averaging 356 ppm U_3O_8 (0.0356%) and 0.6 ppm Au was recorded from conglomerate of the Hardey Sandstone at **Shady Camp Well**, 20 km west-south-west of Marble Bar.

In the southern part of the Marble Bar Sub-basin near **Limestone Well**, 20 km south-west of Marble Bar, an intersection of 0.25 m averaging 613 ppm U_3O_8 (0.0613%) and 0.02 ppm Au was recorded from the unnamed conglomerate unit above the Kylena Basalt.

In the West Pilbara Sub-basin, International Nickel Australia Ltd intersected 0.5 m averaging 648 ppm U_3O_8 (0.0648%) and 0.12 ppm Au in conglomerates of the Hardey Sandstone at the **Coorbeelie River** area, 130 km south-west of Port Hedland.

In the Hardey Sandstone conglomerates, uranium occurs as fine uraninite grains in thucholite pellets and as brannerite in detrital grains of anatase. The heavy mineral assemblage includes pyrite, monazite, zircon and anatase. Within the unnamed conglomerate unit, uranium occurs in detrital grains composed of intergrowths of illite, uraninite, coffinite and galena. Gold within the Hardey Sandstone conglomerate and the unnamed conglomerate is usually present in only trace amounts.

Carter and Gee (1988) reported that the conglomerates of the Hardey Sandstone and the unnamed unit accumulated between about 2750 Ma and 2700 Ma. The lower Fortescue Group is similar in age to the Witwatersrand Supergroup of South Africa, but it is significantly older than the Canadian Huronian Supergroup (Elliot Lake conglomerate-hosted uranium deposits).

YERRIDA BASIN

Quartz-pebble conglomerates containing traces of uranium and gold occur at the base of the Peak Hill Metamorphics within the Yerrida Basin (Fig. 23). Age-dating of the sequence which overlies the Peak Hill Metamorphics indicates that the quartz-pebble conglomerates are older than 2000 Ma (Carter & Gee, 1988). Drilling to explore for uranium and gold palaeoplacers intersected only very low uranium values (usually <30 ppm U_3O_8) and only minute amounts of gold.

On the basis of stratigraphic correlations, Carter and Gee (1988) suggested that the pyritic quartz-pebble conglomerates at the base of the Peak Hill Metamorphics are equivalent to the conglomerates of the lower Fortescue Group.

HALLS CREEK AREA

In 1954, uranium mineralisation was discovered 35 km north-east of Halls Creek in quartz-pebble conglomerate of the Saunders Creek Formation (Fig. 23) (Dow & Gemuts, 1969). The Saunders Creek Formation is about 200 m thick and consists of quartz, feldspathic and lithic sandstones and conglomerate beds with radioactive horizons (Plumb, 1990; Hoatson, 1993). These rocks outcrop around domes and the total area of exposures is less than 15 km^2.

The Saunders Creek Formation is Palaeoproterozoic in age. The age of the conglomerates is uncertain, but they are older than 1920 Ma (Griffin, 1990; Hoatson, 1993).

The best drill intersection in the conglomerates is 1300 ppm U_3O_8 (0.13%) over 0.1 m, but the majority of grades are below 40 ppm U_3O_8 over 2 m. The uranium mineralisation is mainly thorogummite (Carter & Gee, 1988). Pyrite occurs in the sequence, but there are no descriptions of detrital pyrite.

PILBARA CRATON

Quartz-pebble conglomerates occur in the Lalla Rookh Sandstone and Mosquito Creek Formation, which are the upper sequences of the Gorge Creek Group. Conglomerates usually occur as thin pebble beds. However, coarse pebble conglomerates, tens of metres in thickness, also occur. The conglomerates contain detrital pyrite, which may constitute more than 10% of these rocks. Radioactivity in these conglomerates is due to thorium minerals. Exploration has failed to intersect significant uranium mineralisation (Carter & Gee, 1988). Although high gold values have been recorded from surface sampling, the gold grades in drill intersections are very low. Conglomerates of the Lalla Rookh Sandstone and Mosquito Creek Formation are considered to be approximately 3000 Ma.

KIMBERLEY BASIN

Low-grade thorium–uranium mineralisation occurs at several places in quartz-pebble conglomerate of the King Leopold Sandstone, the lowest unit of the Kimberley Group at the eastern margin of the Kimberley Basin (Hughes & Harms, 1975). Individual conglomerate horizons are usually less than 2 m thick and contain rounded clasts of vein quartz, with minor quartzite, jasper, chert and rare volcanics. The radioactivity is due mainly to thorium (thorogummite and florencite) with small amounts of uranium. Typical grades are 20 ppm U and 550 ppm Th, ranging up to 100 ppm U.

The King Leopold Sandstone is Palaeoproterozoic (ca. 1800 Ma) and hence much younger than typical uranium-bearing quartz-pebble conglomerates. The mineralisation essentially consists of detrital concentrations of thorium minerals containing minor amounts of uranium in solid solution.

APPENDIX 1. CLASSIFICATION SCHEME FOR URANIUM RESOURCES (‘NEA/IAEA SCHEME’)

Definitions of resource categories

The OECD Nuclear Energy Agency (NEA) and International Atomic Energy Agency (IAEA) have a classification scheme for uranium resources.

For the NEA/IAEA scheme, resource estimates are divided into separate categories reflecting different levels of confidence in the quantities reported. The resources are further separated into categories based on the cost of production. *All resource estimates are expressed in terms of metric tonnes (t) of recoverable uranium (U) rather than uranium oxide (U_3O_8).* Estimates refer to quantities of uranium recoverable from mineable ore, unless otherwise noted (see later).

Resources are divided, according to different confidence levels of occurrence, into four categories.

- *Reasonably Assured Resources (RAR)* refer to uranium that occurs in known mineral deposits of delineated size, grade and configuration such that the quantities which could be recovered within the given production cost ranges, with currently proven mining and processing technologies, can be specified. Estimates of tonnage and grade are based on specific sample data and measurements of the deposits and on knowledge of deposit characteristics. Reasonably Assured Resources have a high assurance of existence.
- *Estimated Additional Resources — Category I (EAR-I)* refer to uranium in addition to RAR that is inferred to occur, mostly on the basis of direct geological evidence, in extensions of well-explored deposits, or in deposits in which geological continuity has been established but where specific data, including measurements of the deposits, and knowledge of the deposits’ characteristics are considered to be inadequate to classify the resource as RAR. Estimates of tonnage, grade and cost of further delineation and recovery are based on such sampling as is available and on knowledge of the deposit characteristics as determined in the best known parts of the deposit or in similar deposits. Less reliance can be placed on the estimates in this category than on those in RAR.
- *Estimated Additional Resources — Category II (EAR-II)* refer to uranium in addition to EAR-I that is expected to occur in deposits for which the evidence is mainly indirect and which are believed to exist in well-defined geological trends or areas of mineralisation with known deposits. Estimates of tonnage, grade and cost of discovery, delineation and recovery are based primarily on knowledge of deposit characteristics in known deposits within the respective trends or areas, and on such sampling, geological, geophysical or geochemical evidence as may be available. Less reliance can be placed on the estimates in this category than on those in EAR-I.
- *Speculative Resources (SR)* refer to uranium, in addition to EAR-II, which is thought to exist in deposits discoverable with existing exploration techniques. The resource estimates are generally based on indirect evidence and geological extrapolations. The locations of deposits envisaged in this category can usually be specified only as being somewhere within a given region or geological trend. As the term implies, the existence and size of such resources are speculative.

Cost categories

The cost categories are defined as $40/kg U or less; $80/kg U or less; and $130/kg U or less. Costs are expressed in current US$, i.e. as at 1 January for the current year.

NOTE: It is not intended that the cost categories should follow fluctuations in market conditions.

Conversion from other currencies into US$ should be done using the exchange rates of l January of the current year. All resource categories are defined in terms of costs of uranium recovered at the ore processing plant.

When estimating the cost of production for assigning resources within these cost categories, account must be taken of the following costs:

- the direct costs of mining, transporting and processing the uranium ore;
- the costs of associated environmental and waste management during and after mining;
- the costs of maintaining non-operating production units where applicable; in the case of ongoing projects, those capital costs which remain unamortised;
- the capital cost of providing new production units where applicable, including the cost of financing;
- indirect costs such as office overheads, taxes and royalties where applicable; and
- future exploration and development costs wherever required for further ore delineation to the stage where it is ready to be mined.

Sunk costs are not normally taken into consideration.

Recoverable resources

Resource estimates are expressed in terms of recoverable tonnes of uranium, i.e. quantities of uranium recoverable from mineable ore, as opposed to quantities contained in mineable ore, or quantities in situ. Therefore both expected mining and ore processing losses have been deducted in most cases. In situ resources are recoverable resources in the ground, not taking into account mining and milling losses.

APPENDIX 2. LIST OF AUSTRALIAN URANIUM DEPOSITS AND SIGNIFICANT PROSPECTS

BRECCIA COMPLEX DEPOSITS

Stuart Shelf area of Gawler Craton (SA)
Olympic Dam**[3], Acropolis, Wirrda Well, Oak Dam, Emmie Bluff.

Mount Painter field
Mount Gee, Mount Gee East, Radium Ridge, Armchair-Streitberg, Hodgkinson.

UNCONFORMITY-RELATED DEPOSITS

Alligator Rivers uranium field (NT)
Ranger 1 (No. 1 Orebody*, No. 3 Orebody**, Anomalies 2, 4 and 9), Nabarlek*, Jabiluka 1 and 2, Koongarra, Ranger 68, Ranger 4, Hades Flat, Caramal, Austatom, Beatrice, Gurrigarri, Garrunghar, Mordijimuk, Arrarra, Dam, Twin, 7J.

Rum Jungle uranium field (NT)
Dyson's*, White's*, Rum Jungle Creek South*, White's East, Mount Burton*, Mount Fitch, Kylie, Southeast Kylie, Mount Fitch North, Dolerite Ridge, Rum Jungle Creek, Area 55, Waterhouse, Brodribb, Ella Creek.

South Alligator Valley uranium field (NT)
El Sherana*, El Sherana West*, Rockhole 1*, Rockhole 2*, O'Dwyer's*, Sterrits*, Palette*, Saddle Ridge*, Coronation Hill*, Scinto 5*, Scinto 6*, Koolpin Creek*, Skull*, Sleisbeck*.

Rudall Complex (Paterson Orogen)
Kintyre, Tracy, Lead Hills, Mount Cotten.

Turee Creek area (WA)
Angelo River, Noranda.

Granites–Tanami Inlier (WA)
Killi Killi Hills.

Halls Creek area (WA)
Minor prospects.

Tennant Creek area (NT)
Edna Beryl and Northern Star (minor prospects).

Eyre Peninsula
Ben Boy and other minor prospects.

[3] ** deposits from which uranium is currently being produced
* deposits which were past producers of uranium

SANDSTONE DEPOSITS

Frome Embayment uranium field (SA)
Beverley**, Honeymoon, East Kalkaroo, Yarramba, Gould's Dam (Billeroo West), Paralana A and B, Oban.

Eucla Basin (Eyre Peninsula Region)
Warrior, Wynbring, Yarranna.

Westmoreland–Pandanus Creek uranium field (NT & Qld)
Redtree (Jack, Garee, Langi and the Namalangi lenses), Junnagunna, Huarabagoo, Outcamp, Sue, Mageera.

Amadeus Basin (NT)
Angela, Pamela.

Ngalia Basin (NT)
Bigrlyi, Walbiri, Dingo's Rest, Sunberg, Coonega, Karin.

Gunbarrel Basin (WA)
Mulga Rock (Shogun, Emperor, Ambassador).

Carnarvon Basin (WA)
Manyingee, Bennetts Well.

Canning Basin (WA)
Oobagooma.

Other prospects
Drummond Basin (Qld), Boulia Shelf (Qld), Glen Isla and Malakoff areas (Qld), Bangemall Basin (WA), Gilberton Basin (Qld).

SURFICIAL DEPOSITS

Yilgarn Craton (WA)
Yeelirrie, Lake Way, Lake Maitland, Centipede (Abercrombie and Millepede lenses), Hinkler Well, Dawson Well, Nowthanna, Lake Austin, Thatcher Soak, Lake Mason, Lake Raeside, Windimurra, Cogla Downs, Murchison Downs.

Outside the Yilgarn Craton
Jailor Bore (WA), Lamil Hills (WA), Minindi Creek (WA), Napperby (NT), Currinya (NT).

METASOMATITE DEPOSITS

Mount Isa uranium field (Qld)
Valhalla, Skal, Anderson's Lode, Watta, Warwai, Turpentine, Folderol, Ardmore East, Flat Tyre, Emancipation, Miranda, Surprise, Citation.

METAMORPHIC DEPOSITS

Mary Kathleen uranium field (Qld)
Mary Kathleen*, Rita, Rary, Elaine, Elizabeth-Anne.

VOLCANIC DEPOSITS

Georgetown–Townsville uranium field (Qld)
Ben Lomond, Maureen, Turtle Arm, Dagworth, Fiery Creek, Trident, Phillips Well, Laura Jean, Oasis, Lineament Group, Chinaman Creek, Limkins, Mount Hogan, Werrington Group, Kaiser Bill, Quest-End.

INTRUSIVE DEPOSITS

Olary uranium field (SA)
Radium Hill*, Mount Victoria, Crocker Well, Crocker Well East, Spring Hill, Thackaringa.

Gascoyne Complex (WA)
Mortimer Hills.

Strangways Range, central Australia (NT)
Mordor Igneous Complex.

VEIN DEPOSITS

Other occurrences
Mundong Well (WA); Lincoln Complex, Haughton, Myponga*, Last Chance (SA); Blackfellows Dam, Carcoar, Emmaville, Gilgai, Gordonbrook, The Gulf, Torrington, Watsons Creek, Whipstick (NSW); Mount Kooyoora, Lake Boga, Wycheproof, Sunnyside Goldfield (Vic.); Royal George, Chwalczyks, Anchor, Heemskirk (Tas.).

Pandanus uranium field (NT)
Eva Deposit* (Pandanus Creek), Cobar 2*, El Hussen.

QUARTZ-PEBBLE CONGLOMERATE DEPOSITS

Hamersley Basin (WA)
Bonnie Creek, Shady Camp Well, Warralong Creek, Limestone Well, Coorbeelie River.

Yerrida Basin
Traces of uranium and gold in Peak Hill Metamorphics.

Halls Creek area (WA)
Saunders Creek Formation.

Pilbara Craton
Gold mineralisation in conglomerates of the Lalla Rookh Sandstone and Mosquito Creek Formation.

Kimberley Basin (WA)
King Leopold Sandstone.

APPENDIX 3. OWNERSHIP OF URANIUM MINES AND MAJOR DEPOSITS AS AT JULY 2000

Northern Territory	
Ranger, Jabiluka	Energy Resources of Australia Ltd (operating company), owned (August 2000) by mining companies in the following proportions: Peko Wallsend Ltd (36.14%); North Ltd* (35.94%); Cameco Resources Australia Pty Ltd (6.45%); UG Australia Developments Pty Ltd (4.12%); Interuranium Australia Pty Ltd (1.98%); Cogema Australia Pty Ltd (1.31%); OKG Aktiebolag (0.54%); Japan Australia Uranium Resources Development Company Ltd (10.64%); others (2.88%) * In August 2000, Rio Tinto Ltd gained control of North Ltd. North controlled 68.4% of Energy Resources of Australia Ltd through direct equity and indirectly through equity in Peko Wallsend Ltd.
Koongarra	Cogema Australia Pty Ltd
Ngalia Basin (Bigrlyi, Walbiri & others)	Samantha Mining & Exploration Pty Ltd (41.71%); Yuendumu Mining Company Ltd (35.81%); Central Pacific Minerals NL (17.48%); Southern Cross Exploration NL (5.00%)
Angela, Pamela	Black Range Minerals
South Australia	
Olympic Dam	WMC Ltd
Beverley	Heathgate Resources Pty Ltd (an affiliate of General Atomics, a United States company)
Honeymoon, East Kalkaroo, Goulds Dam	Southern Cross Resources Australia Pty Ltd
Western Australia	
Kintyre	Rio Tinto Ltd
Yeelirrie	WMC Ltd
Lake Way	Normandy Mining Ltd
Manyingee, Oobagooma	Paladin Energy Minerals NL
Mulga Rock	PNC Exploration (Australia) Pty Ltd
Lake Maitland, Centipede	Acclaim Uranium NL
Queensland	
Westmoreland	Mining leases and exploration titles were relinquished by Rio Tinto in March 2000. As at December 2000, there were no tenements or licence applications over the deposits.
Ben Lomond, Maureen	Anaconda Uranium Corporation
Valhalla, Skal	Summit Resources NL (50%); Resolute Ltd (50%)

APPENDIX 4. COMPOSITIONS OF URANIUM AND RELATED MINERALS MENTIONED

Autunite	$Ca(UO_2)_2(PO_4)_2.10\text{-}12H_2O$
Bassetite	$Fe(UO_2)_2(PO_4)_2.8H_2O$
Beta-uranophane	$Ca(UO_2)_2Si_2O_7.6H_2O$
Brannerite	$(U,Ca,Ce)(Ti,Fe)_2O_6$
Carnotite	$K(UO_2)_2(VO_4)_2.3H_2O$
Coffinite	$U(SiO_4)_{1-x}(OH)_{4x}$
Curite	$Pb_2U_5O_{17}.4H_2O$
Davidite	$A_6B_{15}(O,OH)_{36}$, where A = Fe^{+2}, rare earths, U, Ca, Zr and Th; and B = Ti, Fe^{+3}, V and Cr
Gummite	General term for yellow, orange, red, or brown secondary minerals consisting of mixtures of hydrous oxides of uranium and thorium; an alteration product of uraninite
Iriginite	$U(MoO_4)_2(OH)_2.2H_2O$
Johannite	$Cu(UO_2)_2(SO_4)_2(OH)_2.6H_2O$
Kasolite	$Pb(UO_2)SiO_4.H_2O$
Meta-autunite	$Ca(UO_2)_2(PO_4)_2.26H_2O$
Metatorbernite	$Cu(UO_2)_2(PO_4)_2.8H_2O$
Meta-uranocircite	$Ba(UO_2)_2(PO_4)_2.8H_2O$
Monazite	$(Ce,La,Nd,Th)(PO_4,SiO_4)$
Phosphuranylite	$Ca(UO_2)_4(PO_4)_2(OH)_4.7H_2O$
Pitchblende*	UO_2
Renardite	$Pb(UO_2)_4(PO_4)_2(OH)_4.7H_2O$
Sabugalite	$H,Al(UO_2)_4(PO_4)_4.16H_2O$
Saleeite	$Mg(UO_2)_2(PO_4)_2.8H_2O$
Sklodowskite	$Mg(UO_2)Si_2O_7.6H_2O$
Soddyite	$(UO_2)_5Si_2O_9.6H_2O$
Thorogummite	$Th(SiO_4)_{1-x}(OH_4)_x$ (may contain up to 31.4% U)
Thucholite	A complex of organic matter (hydrocarbons) and uraninite; usually contains thorium
Torbernite	$Cu(OU_2)_2(PO_4)_2.8\text{-}12H_2O$
Tyuyamunite	$Ca(UO_2)_2(VO_4)_2.5\text{-}8H_2O$
Umohoite	$(UO_2)MoO_4.4H_2O$
Uraninite*	UO_2
Uranophane	$Ca(UO_2)_2Si_2O_7.6H_2O$
Xenotime	$(Y,Ce,Th,U)PO_4$

Source: *AGI Glossary of Geology,* American Geological Institute, Falls Church, Virginia.

* Uraninite (euhedral uranium oxide) and pitchblende (colloform uranium oxide) can be distinguished on the basis of their physico-chemical parameters as follows (Fritsche & Dahlkamp, 1997):

	Uraninite	**Pitchblende**
Habit	Euhedral	Colloform, amorphous
Unit-cell dimension (Angstrom units, Å)	> 5.46	< 5.46
Oxidation grade	$< UO_{2.2}$	$> UO_{2.2}$
CaO content	< 1.5 weight %	1–5 weight %
ThO_2 content	up to several weight %	< 1 weight %

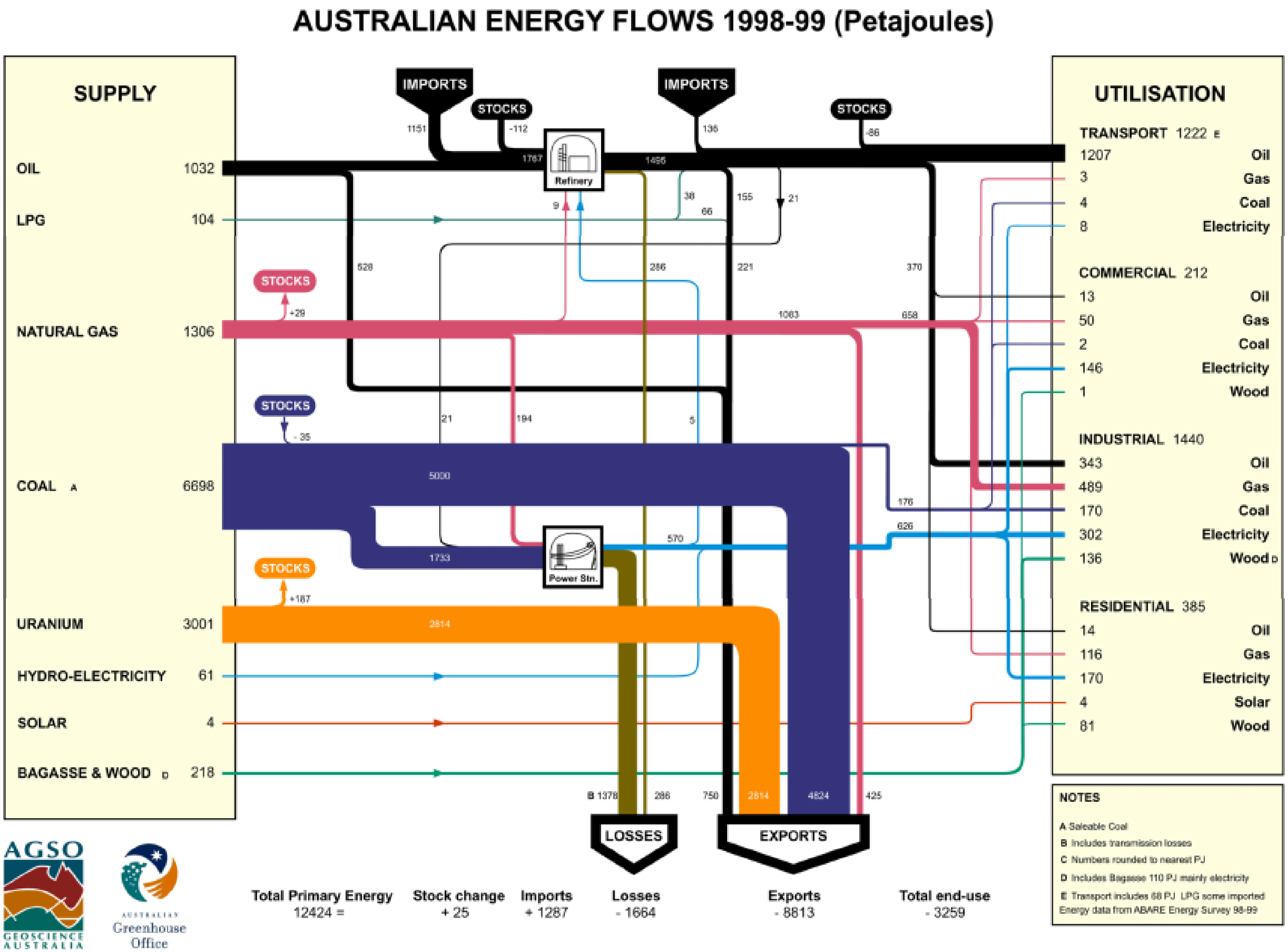

Figure 44. Australian energy flows 1998–99 (figure reproduced with permission of Australian Greenhouse Office, Commonwealth Department of Environment and Heritage)

APPENDIX 5. URANIUM AND NUCLEAR ELECTRICITY

All of Australia's uranium production is exported for use in nuclear power stations to generate electricity. In 2000, Australia exported 8757 t U_3O_8 (7426 t U). Approximately one third of these exports went to Japan, a further one third to the United States and the remainder to Belgium, Canada, Finland, France, United Kingdom, South Korea and Sweden. All exports are subject to IAEA safeguards agreements and Australia's network of bilateral nuclear safeguards agreements.

Australia's exports of energy commodities in 1998–99 were 169.41 Mt coal (coking and steaming), 5079 t U (5989 t U_3O_8), 16 777 ML crude oil, refinery products and liquefied petroleum gas, and 7.82 Mt liquefied natural gas (ABARE, 2000). Figure 44 shows the 1998–99 exports measured in terms of contained energy (in petajoules PJ). Uranium exports contained 2814 PJ which represented 32% of Australia's total energy exports.

World requirements of uranium for electricity generation amount to approximately 60 000 t U annually (Table 27). With a total production capacity of 9400 t U, Australia's three uranium mines (Olympic Dam, Ranger and Beverley) have the capacity to supply approximately 16% of annual world requirements of uranium for electricity generation.

Table 27. Nuclear energy data for 1999 (OECD/NEA, 2000)

	World	OECD
Number of countries generating nuclear electricity	31	16
Number of nuclear generating units in operation	434	348
Nuclear electricity generation (terawatt hours)	2 401	2 075
Nuclear share in electricity generation (%)	17	24
Uranium requirements (t U)	60 000	50 000
Carbon dioxide emissions avoided* (Mt CO_2)	1 920	1 660

*estimated assuming that each kilowatt-hour of electricity generated by coal emits 800 grams of CO_2

In 1999, approximately 17% of the world's electricity was generated by nuclear power. Nuclear power produces no greenhouse gases. A single large nuclear power plant of one gigawatt (electrical) capacity avoids the emissions of about 1.75 Mt of carbon dioxide each year if it displaces coal, about 1.2 Mt if it displaces oil and 0.7 Mt if it displaces natural gas (OECD/NEA, 2000).

A major international effort is in progress to understand the scientific aspects of climate change and to identify measures to alleviate and mitigate the effects of these changes. The United Nations Framework Convention on Climate Change (FCC) is a major step towards controlling and limiting greenhouse gas emissions. Within the FCC, the Kyoto Protocol of December 1997 seeks to impose binding commitments on the developed countries to reduce their greenhouse gas emissions below 1990 levels by 2008–12. It is generally considered that meeting the Kyoto targets will pose a challenge for many countries (OECD/NEA, 2000).

Although nuclear energy presents advantages in terms of reduced greenhouse gas emissions, there are ongoing concerns about nuclear waste disposal. Worldwide there has been a mixed response to the use of nuclear energy. While most of the world's nuclear energy is currently generated within the OECD countries, most of the future growth in nuclear capacity is likely to occur in non-OECD countries. A total of thirty-one new reactors are under construction worldwide, though in recent years the growth in nuclear power has slowed considerably. Issues relating to public acceptance will continue to be major factors in the future development of nuclear energy.

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