Australia's URANIUM resources, geology and development of deposits

A.D. McKay and Y. Miezitis

AGSO GEOSCIENCE AUSTRALIA

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Front cover: Aerial view of the Olympic Dam mine, South Australia. Photo courtesy of WMC (Olympic Dam Corporation) Pty Ltd.

Back cover: Uranium recovery plant, Beverley mine, South Australia. Large diameter trunk lines carry leach solutions from the plant to the wellfield, and leachate containing dissolved uranium from the wellfield to the plant. Photo courtesy of Heathgate Resources Pty Ltd.

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ABSTRACT

Virtually all of Australia's significant uranium deposits were discovered between 1969 and 1980 during the period of high expenditures on exploration for this commodity. This was followed by a long period of low exploration expenditures from 1982 onwards, during which only one deposit (Kintyre) was discovered. Estimates of Australia's uranium resources continued to increase after 1982 only because of on-going delineation of resources at the known deposits.

Australia's uranium resources at December 2000, within the Reasonably Assured Resources (RAR) category recoverable at ≤US$40/kg U, were estimated by AGSO – Geoscience Australia to be 654 000 t U. These resources are more than any other country has reported, to date, in this category. Most of these resources are in six deposits:

- Olympic Dam (South Australia);
- Ranger, Jabiluka, Koongarra in the Alligator Rivers region (Northern Territory);
- Kintyre and Yeelirrie (Western Australia).

Australia has the world's largest (29%) resources in RAR recoverable at ≤US$80/kg U (includes resources in ≤US$40 category) with 667 000 t U in this category. According to uranium resource figures published by the mining companies (as distinct from the OECD/NEA and IAEA resource categories defined in Appendix 1), more than 80% of Australia's uranium resources occur in two main types of deposits and about 97% are in four types of deposits:

- Breccia complex deposits contain about 65% of Australia's total uranium resources and nearly all of these resources are at Olympic Dam, which is the world's largest uranium deposit.
- Unconformity-related deposits account for about 20% of Australia's total resources, mainly in the Alligator Rivers field (Ranger, Jabiluka, Koongarra), and in one deposit in the Rudall Province, Western Australia (Kintyre).
- Sandstone uranium deposits account for about 7% of Australia's total resources, mainly in the Frome Embayment field, South Australia (Beverley, Honeymoon, East Kalkaroo, Goulds Dam) and the Westmoreland area, Queensland (Redtree, Junnagunna, Huarabagoo). Other significant sandstone type deposits include Manyingee, Mulga Rock and Oobagooma in Western Australia, and Angela in Northern Territory.
- Surficial (calcrete) deposits have about 5% of Australia's resources, most of which are in the world class Yeelirrie deposit. Other calcrete deposits include Lake Way, Lake Maitland and Centipede (Western Australia).

Other types of uranium deposits in Australia include metasomatite deposits (Valhalla, Skal and Anderson's Lode, Queensland) with approximately 1.5% of Australia's total uranium resources. Australia has only small resources within metamorphic (remnant resources at Mary Kathleen, Queensland), volcanic (Ben Lomond, Maureen, Queensland) and intrusive deposits (Crocker Well, Mount Victoria, South Australia). Australia has no significant deposits of the quartz-pebble conglomerate type, vein type and collapse breccia pipe type.

During the main period of uranium production in Australia, commencing in 1976, Australia's share of annual world production increased from approximately 1% (365 t U) in 1977 to 22% (7579 t U) in 2000. In 2000, Australia was the world's second largest producer of uranium. All of Australia's uranium production is exported to countries in North America, East Asia and Europe for use as fuel in nuclear power stations to generate electricity.

Australia now has three operating uranium mines: Olympic Dam, Ranger and Beverley. The proposal for a new mine at Honeymoon is in the final stages of an environmental impact assessment process. A major expansion of the Olympic Dam operations was completed in early 1999. The Beverley operation,

Australia's first in situ leach uranium mine, commenced production in November 2000. In 1998 the Jabiluka project received approval for development following an environmental impact assessment process that lasted almost three years. A decline from the surface has been completed, and initial underground development commenced in 1999. However, the project is currently in a stand-by and environmental care and planning phase.

Proponents of new uranium mines in Australia are required by legislation to complete a comprehensive environmental impact assessment process, which calls for public comments on the proposal. The projects are assessed jointly by Commonwealth and State/Territory Government agencies. For approval, the projects must meet strict requirements for environmental, heritage and nuclear safeguards.

Exploration for uranium in Australia has been influenced by changes in government policies and incentives, market prices and demand, social factors, legislation (including Aboriginal Land Rights and Native Title Acts), and advances in exploration technologies. Commonwealth and State/Territory Government policies on uranium have been the major influences on exploration since the late 1960s.

The main areas of uranium exploration during the late 1990s included:

- Arnhem Land (Northern Territory) – exploration for unconformity-related deposits in Palaeoproterozoic metasediments below a thick cover of Kombolgie sandstone; this region is highly prospective for large high-grade deposits along the unconformity (similar to Cigar Lake deposit in the Athabasca Basin, Canada);
- Paterson Province (Western Australia) – exploration for unconformity-related deposits in Palaeoproterozoic metasediments of the Rudall Metamorphic Complex which hosts the Kintyre orebody;
- Frome Embayment (South Australia), and Carnarvon Basin (Western Australia) – exploration for sandstone uranium deposits;
- Olympic Dam area – exploration for breccia complex deposits in Mesoproterozoic granitoids of the Gawler Craton below the Stuart Shelf sedimentary sequence;
- Westmoreland area (north-west Queensland) – exploration for sandstone-type deposits in Proterozoic sediments of the McArthur Basin;
- Tertiary palaeochannel sediments overlying the Yilgarn Craton (Western Australia) – exploration for calcrete deposits.

INTRODUCTION

Since the report *Australian Uranium Resources* (Battey, Miezitis & McKay, 1987) was released by the Bureau of Mineral Resources, Geology and Geophysics (BMR), there have been many changes in the Australian uranium mining industry. As a result, a great deal of information has become available about resources and the geology of uranium deposits. This report reviews and updates the 1987 BMR report.

Since 1987, production and known resources have increased in Australia and expenditure on exploration has decreased, government policy has changed and there have been several new mine proposals. Meanwhile, worldwide demand for uranium for electricity generation has risen.

At the Olympic Dam mine in South Australia, production began in 1988 and has progressively expanded, with the mine becoming Australia's largest uranium producer (in terms of annual production) by 2000. At Ranger, mining was completed at the No. 1 Orebody in 1994, and commenced at No. 3 Orebody in 1996. At the Beverley in-situ leaching mine, production commenced in November 2000. At Nabarlek, the mine was closed in 1988. Overall, Australia's known uranium resources in the Reasonably Assured category recoverable at ≤US$80/kg U have increased from 470 000 t U in 1987 to 667 000 t U in 2000.

Exploration expenditure for uranium has declined since 1987, reaching a very low level in 1994 and 2000. Since 1985 no new uranium deposits have been found in Australia.

There have been important changes to Commonwealth Government policies relating to the mining and export of uranium. In 1983, the Commonwealth Labor Government had introduced a policy that became known as the 'Three mines' policy, permitting only the Nabarlek, Ranger and Olympic Dam mines to export uranium. The 'Three mines' policy was abolished by the Liberal–National Party Coalition upon election to Government in March 1996. This cleared the way for the development of new uranium mines, provided they comply with strict environmental, heritage and nuclear safeguards requirements. Also in 1996, the Foreign Investment Review Board guidelines relating to foreign investment in Australian uranium mining were eased, allowing foreign companies a higher percentage ownership of individual uranium mining projects.

After these changes in policies, proposals were submitted for development of new uranium mines at Jabiluka, Beverley, Honeymoon and Kintyre and for a major expansion of the Olympic Dam mine. In addition there was drilling and resource evaluation at a number of deposits including Goulds Dam, Westmoreland, Manyingee, Valhalla and several calcrete deposits. Following rigorous environmental impact assessments under the *Environmental Protection (Impact of Proposals) Act 1974*, Government approvals were granted for development of Jabiluka and Beverley and the Olympic Dam expansion, subject to a range of environmental requirements. The Olympic Dam expansion project was completed in 1999. Construction of a commercial in situ leach operation at Beverley was completed and production commenced in November 2000, as already mentioned. The initial stages of development of Jabiluka have been completed; and the environmental impact statement for the Honeymoon in situ leach project was being assessed at the time of writing this report.

The new projects have received a great deal of attention from government and the public, and the issues arising demonstrate the high level of public scrutiny and environmental protection that can be expected at new uranium mines in Australia.

Uranium mining has been the focus of considerable public debate in Australia for many years. The first inquiry into uranium mining was the Ranger Uranium Environmental Inquiry, conducted by Justice Fox between 1975 and 1977 (Fox, Kelleher & Kerr, 1976 & 1977). This major government inquiry considered proposals for the development of new mines and the export of Australian uranium, and its findings allowed the development of the mines at Nabarlek and Ranger in the Alligator Rivers region (Northern Territory).

More recently, Australia's uranium mining sector was the subject of a review by the Senate Select Committee on Uranium Mining and Milling, which tabled its report in the Senate in May 1997. The Committee's majority report stated that the main findings of the 1977 Ranger Uranium Environmental Inquiry (the Fox Report) remained valid as the foundation for policy on the mining and milling of uranium in Australia. The main findings and recommendations of the Fox Report (Fox & others, 1976, page 185) were that:

> The hazards of mining and milling uranium, if those activities are properly regulated and controlled, are not such as to justify a decision not to develop Australian uranium mines.

Since the mid-1970s, the demand for uranium as fuel for nuclear power stations has increased progressively. During 1999, nuclear power stations provided 17% of the world's electricity requirements (24% of the requirements in OECD (Organisation for Economic Cooperation and Development) countries). World requirements of uranium for nuclear electricity generation are approximately 60 000 t U (71 000 t U_3O_8) annually. The OECD Nuclear Energy Agency (NEA) estimated that the nuclear electricity generated during 1999 avoided the emission of 1920 Mt of carbon dioxide that would have been released to the atmosphere had the same quantity of electricity been generated by coal-fired power stations (OECD/NEA, 2000). Appendix 5 discusses this further.

The development and growth in nuclear power globally has resulted from decisions made in the 1970s during a sustained period of rapidly increasing oil prices which caused an energy crisis in many countries. Overly optimistic projections of the growth of nuclear power worldwide led to the commitment of large exploration expenditures during the 1970s and early 1980s to search for new uranium resources. Successful exploration in Australia discovered new uranium provinces and deposits. Uranium resources increased rapidly to the extent that Australia now has the world's largest known resources of uranium.

Australia has no significant national demand for uranium and all production is exported. Australia applies stringent conditions to the export of uranium to ensure it is used only for peaceful purposes. These conditions — referred to as nuclear safeguards — require customer countries to allow international inspectors from the International Atomic Energy Agency (IAEA) to verify that the uranium is not directed into weapons programs. In addition, Australia requires compliance with parallel conditions under treaties it has concluded with end customer countries. This compliance is monitored by the Australian Safeguards and Non-Proliferation Office.

EXPLORATION AND DISCOVERY

The occurrence of uranium in Australia was known long before the start of any systematic exploration for it. Uranium was first recorded in Australia from Carcoar (NSW) in 1894, where torbernite was found with cobalt mineralisation. Two relatively significant occurrences of uranium were discovered at Mount Painter (South Australia (SA) in 1906, and at Radium Hill (SA) in 1910 (Fig. 1) (AAEC, 1962).

Historically there have been two main phases of uranium exploration in Australia:

- 1944 to late 1950s,
- 1966 onwards.

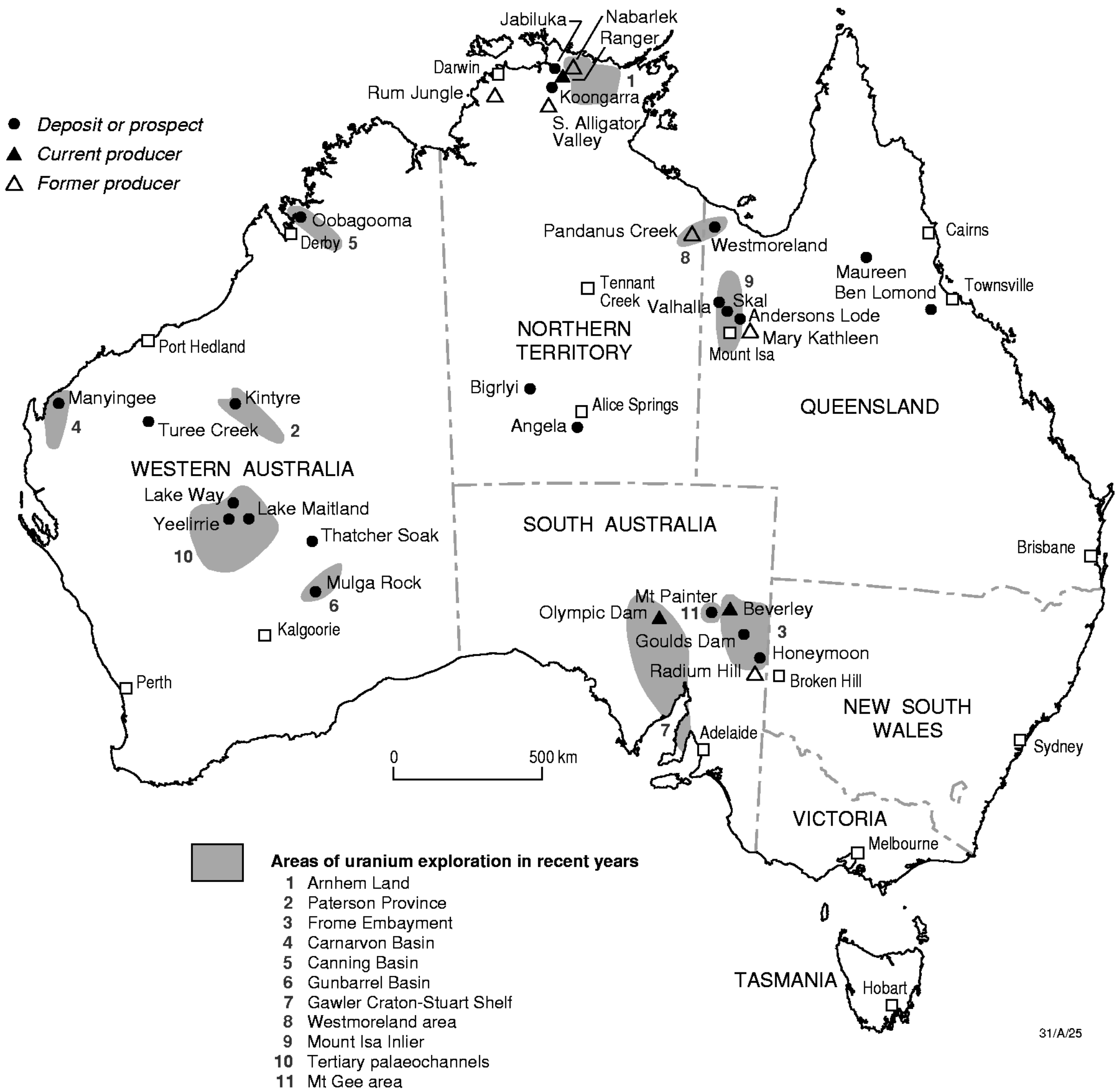

Figure 1. Australian uranium deposits and prospects, and areas of uranium exploration in recent years

Exploration from 1944 to late 1950s

Exploration for uranium in Australia started in 1944 in response to requests from the United Kingdom and United States Governments. The known deposits at Mount Painter and Radium Hill were examined by South Australian and Commonwealth Government geologists. To promote exploration, the Commonwealth Government introduced tax-free rewards in 1948 for the discovery of uranium orebodies. Additional inducements to explore and develop uranium resources were introduced in 1949 when a five-year uranium ore-buying pool in Australia was approved, to guarantee fixed prices for uranium ore. In 1952, tax breaks were introduced for profits earned in uranium mining and treatment (AAEC, 1962). This stimulated the search, particularly around known mineral fields.

In some areas there was feverish activity akin to the gold rushes of last century. Uranium was discovered at Rum Jungle (Northern Territory (NT)) in 1949, in the South Alligator Valley (NT) in 1953, at Mary Kathleen (Queensland (Qld)) in 1954 and at Westmoreland (Qld) in 1956 (Fig. 1). Minor occurrences were found at many places across the continent. Sums totalling the equivalent of about A$225 000 were paid to 35 prospectors under the reward scheme. Most of the significant discoveries during this period were made by prospectors using geiger counters. As the existing sales contracts became filled there seemed little prospect for further sales, and exploration virtually ceased in the late 1950s (Battey & Hawkins, 1978).

Exploration from 1966 onwards

Annual surveys of uranium exploration in Australia have been carried out since the late 1960s by Commonwealth Government agencies including the Australian Atomic Energy Commission, Bureau of Mineral Resources, Geology and Geophysics (BMR), Bureau of Resource Sciences, and Australian Geological Survey Organisation. The results of these surveys are summarised in Table 1.

Table 1. Uranium exploration expenditure and drilling, 1967 onwards

Year	Exploration expenditure Current A$ million	Constant 2000 A$ million	Drilling[a] '000 m	Year	Exploration expenditure Current A$ million	Constant 2000 A$ million	Drilling[a] '000 m
1967	1	7.93	n.a.	1984	13	24.98	77
1968	3	23.20	n.a.	1985	13	23.41	56
1969	6	45.00	n.a.	1986	18	29.71	100
1970	8	57.88	n.a.	1987	24	36.53	143
1971	9	61.15	n.a.	1988	26.44	36.88	173.52
1972	13	83.71	n.a.	1989	22.04	29.08	115.43
1973	11	64.73	n.a.	1990	15.74	19.36	105.85
1974	11	56.13	n.a.	1991	14.26	16.99	93.11
1975	8	35.52	65	1992	13.56	16.00	77.79
1976	13	50.76	168	1993	8.28	9.60	37.03
1977	17	59.06	240	1994	6.67	7.59	12.38
1978	25	80.49	335	1995	8.26	8.97	16.13
1979	29	85.74	274	1996	14.92	15.80	19.29
1980	35	93.99	489	1997	23.63	24.95	63.42
1981	38	92.91	425	1998	19.37	20.27	78.09
1982	29	63.80	254	1999	9.61	9.91	33.13
1983	14	27.95	101	2000	7.59	7.59	19.29

n.a. not available.

Note: The aggregate amount of drilling from 1967 to 1971 was 573 000 m.

[a] Includes diamond core, percussion and auger drilling

The increases in uranium exploration from 1966 onwards were due mainly to the very strong perception that the use of nuclear power for the generation of electricity would escalate sharply. The Commonwealth Government relaxed the existing export policy for uranium in 1967 to encourage exploration, and as a result uranium exploration expenditure increased rapidly during 1967–72 (Fig. 2). Worldwide, there was increased uranium exploration associated with the first oil shock in 1973 when the Organisation of Petroleum Exporting Countries (OPEC), operating as a cartel, reduced supply, causing sharp increases in crude oil prices. In response, many countries began developing nuclear power programs as an alternative to oil for electricity generation.

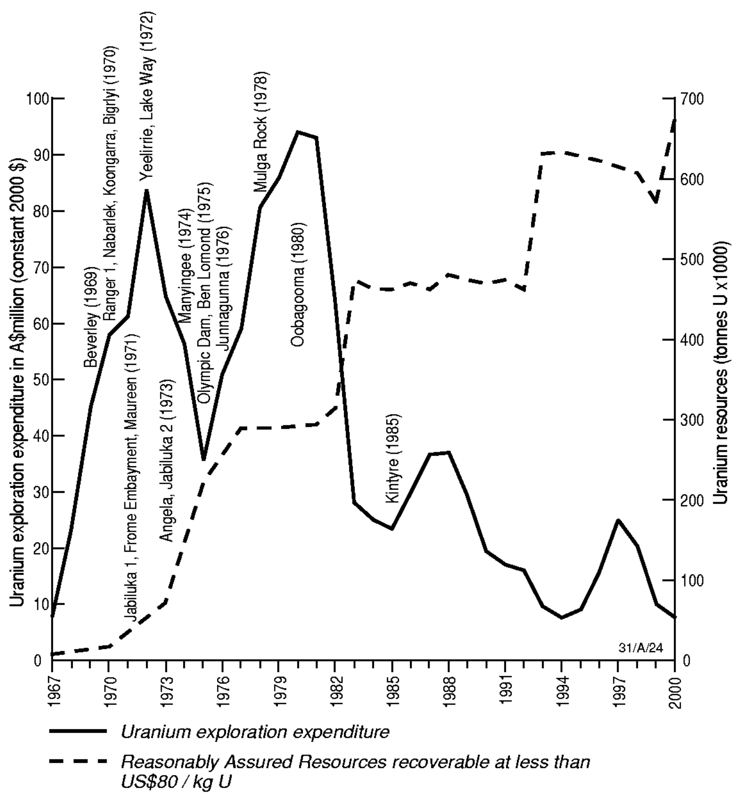

Figure 2. Comparison between annual expenditures on uranium exploration and the discovery of deposits and growth in Australia's uranium resources

In Australia, however, uranium exploration expenditure diminished during the period 1972 to 1975 because the policies of the then Labor Government actively discouraged uranium exploration by private companies. During the latter part of this period Government-funded exploration for uranium was carried out by the Australian Atomic Energy Commission, and the Government purchased a major equity in the Ranger deposit and the Mary Kathleen mine. The period from 1972 to 1975 was also a period of declining exploration for all minerals in Australia after the 'mining boom' of the late 1960s.

Following the election of the Liberal–National Party Coalition to Government in late 1975, exploration rose progressively to a record level of A$94 million (in constant 2000 A$) in 1980. Some of the factors which caused this resurgence of uranium exploration were:

- release in 1976 and 1977 of findings from the Ranger Uranium Environmental Inquiry; and the Government's announcement of Australia's uranium policy in 1977, which cleared the way for continuing development of the uranium mining industry in Australia under strictly controlled conditions;

- sharp rises in uranium spot market prices, resulting from overly optimistic forecasts of the future growth in nuclear power generation. Spot market prices rose to peak levels in 1976. Prices negotiated for sales under long-term contracts also increased from the mid-1970s;
- increases in crude oil prices associated with the second oil shock in 1979.

In contrast to the earlier exploration for uranium by prospectors, the exploration from 1966 onwards was undertaken by major companies using advanced exploration techniques and equipment, and with large exploration budgets. The development of multi-channel gamma ray spectrometers with large volume crystal detectors increased the effectiveness of airborne radiometric surveys.

During the 1970s, exploration and mapping resulted in a much better understanding of the distribution of uranium, and consequently the search could be focused more effectively on geological environments considered likely to contain uranium deposits. The regional mapping by BMR and the State geological surveys was used effectively by exploration teams in the selection of areas, and companies conducted airborne radiometric surveys using multi-channel gamma ray spectrometers. This exploration was highly successful and virtually all of Australia's significant deposits were discovered during the period 1969 to 1980 (Fig. 2).

Important discoveries during this period were the unconformity-related deposits of Ranger, Jabiluka, Nabarlek and Koongarra in the Alligator Rivers area of NT; Olympic Dam, Beverley and Honeymoon in SA; and Yeelirrie in Western Australia (WA) (Fig. 1). These discoveries were significant for two main reasons. First, discovery of the unconformity-related uranium deposits in the Alligator Rivers region completely changed the geological targets emphasised for uranium exploration (Borschoff, 1998); before these discoveries, the major resources were in lower grade and less economic sandstone-type deposits. Second, the discovery of the Olympic Dam deposit (breccia complex type), which is the world's largest deposit of low-cost uranium, initiated exploration in most western world countries for this type of mineralisation. By the mid-1980s, these discoveries had increased Australia's resources of low-cost uranium to approximately 30% of the western world's resources in this category.

From the peak level in 1980, uranium exploration expenditure declined sharply to A$28 million (in constant 2000 A$) in 1983. This was because of recession in the major industrial nations; the implementation of energy conservation policies in response to the oil shocks; and a sharp fall in uranium spot market prices from 1976 onwards (McKay, 1998). Uranium exploration worldwide declined similarly during the early 1980s.

In 1983 the Labor Government introduced the 'Three mines' policy. Under this policy, exports of uranium were permitted only from the Nabarlek, Ranger and Olympic Dam mines. Also, during the early 1980s, the Victorian and New South Wales State Governments introduced legislation to prohibit exploration and mining of uranium: consequently there has been no uranium exploration in these States since then.

Despite the dampening effect of the 'Three mines' policy on uranium exploration, the discovery of the Kintyre deposit (Paterson Province, WA) in 1985 led to an increase in exploration expenditure during 1985–88. This was aimed at locating similar deposits elsewhere in the Paterson Province. Exploration subsequently declined from 1989 onwards to a historical low in 1994.

Spot market prices for uranium fell for almost 16 years from 1978 (peak levels) to 1994. During the early 1990s (1990–94), prices reached very low levels — in the range US$7–10/lb U_3O_8 in current US dollars. This drop in prices was mainly caused by a build-up of excess uranium inventories in western world countries, and by the breakdown in segregation between western and former eastern bloc markets from 1989 onwards, resulting in uranium from the former USSR being sold on world markets.

The Commonwealth Government introduced the *Native Title Act 1993* in January 1994. The Act requires exploration companies to notify and negotiate with Native Title parties before exploration tenements can be granted over lands where Native Title exists, or which are subject to a registered Native Title claim. The Act requires that complementary State/Territory legislation be formulated — a process which has delayed the approval of exploration licence applications for all minerals including uranium. This has had a marked impact on uranium exploration in Western Australia where large areas of Crown lands are affected by Native Title land claims.

Uranium exploration increased after the Liberal–National Party Coalition abolished the 'Three mines' policy in 1996. There was also improved demand for uranium. However, exploration subsequently declined during 1998 and 1999 when several large companies stopped exploration for uranium in Australia as low prices continued.

During the latter part of the 1990s, two factors strongly influenced the focus of uranium exploration. First, the economic success of both the Ranger mine (unconformity-related deposit) and the Olympic Dam mine (breccia-complex-type deposit) confirmed that these types of uranium deposits are important exploration targets. Second, successful development during the last decade, in the United States, of low-cost in situ leach technology for mining sandstone uranium deposits reactivated the search for this type of deposit.

The main areas where uranium exploration was carried out during the late 1990s (Fig. 1) included:

- Arnhem Land (NT) — exploration for unconformity-related deposits in Palaeoproterozoic metasediments below a thick sandstone cover of the Kombolgie Subgroup. This region is regarded by some exploration companies as one of the most prospective and under-explored regions in the world (Borschoff, 1998).
- Paterson Province (WA) — exploration for unconformity-related deposits in Palaeoproterozoic metasediments of the Rudall Metamorphic Complex, which hosts the Kintyre orebody;
- Frome Embayment (SA), Carnarvon, Canning and Gunbarrel Basins (WA) — exploration for sandstone uranium deposits;
- Olympic Dam area — exploration for breccia-complex-type deposits in Mesoproterozoic granitoids of the Gawler Craton below the Stuart Shelf sedimentary sequence;
- Westmoreland area (north-west Queensland) — exploration for sandstone-type deposits in Proterozoic sediments of the McArthur Basin;
- Mount Isa Inlier — exploration for metasomatite-type deposits in Proterozoic metasediments;
- Tertiary palaeochannel sediments overlying the Yilgarn Craton (WA) — exploration for calcrete-type deposits;
- Mount Gee area — exploration for breccia complex deposits in Palaeozoic hematite breccias.

In summary, the exploration for uranium in Australia has been influenced by a number of factors, including changes in government policies and incentives, market prices and demand, social factors (including the Aboriginal Land Rights Act and the Native Title Act), and advances in exploration technologies. Since the late 1960s, Commonwealth and State Government policies on uranium have been overwhelmingly the major influences on exploration expenditure. The period of elevated exploration expenditures, 1969 to 1980, during which most of Australia's significant deposits were discovered, has been followed by a long period of low expenditure since 1982 which has yielded only one new deposit (Kintyre). Although Australia's known low-cost resources have continued to increase during this period, it has only been due to the delineation of resources at the known deposits.

DEVELOPMENT AND PRODUCTION

Uranium was first recovered in Australia as a by-product of ore mined for radium at Radium Hill and Mount Painter (SA). Records show that about 2000 t ore was treated, and the uranium content had minor commercial interest for use in ceramic glazes. As only a fraction of the uranium content of the ore was recovered, this production can be considered insignificant.

First phase (1954–71)

Between 1954 and 1971 Australia produced some 7732 t U (Table 2) from plants at five locations (Warner, 1976). The mines were developed to satisfy contracts with the United Kingdom Atomic Energy Authority (UKAEA) and the Combined Development Agency, the joint UK–USA uranium purchasing agency. Capital investment in mining and treatment (in current A$) amounted to about $50 million, and exports earned some $164 million. The first phase of uranium production in Australia ceased after the closure of the Rum Jungle plant in 1971.

Table 2. First uranium production phase, 1954–71 (t U)

	Rum Jungle (NT)	Radium Hill (SA)[c]	Mary Kathleen (Qld)	South Alligator Valley (NT)	
				United Uranium NL	S. Alligator Uranium NL
Production began	1954	1954	1958	1959	1959
Production ended	1971	1962	1963	1964	1962
Mining method	Open cut	Underground	Open cut	Open cut and underground	Underground
Ore treated (t)	863 000[a]	970 000	2 947 000	128 000[f]	13 500
Average grade (% U)	0.24–0.34[b]	0.59–0.76[d]	0.20[e]	0.30–0.58[g]	0.95
Production (t U)	2 993	721	3 460	441[g]	117
Export contract					
Purchaser	CDA	CDA	UKAEA	UKAEA[h]	UKAEA
Quantity (t U)	1 255	721	3460	441[h]	100

Source: Warner (1976).
(a) In addition, 275 000 t Cu–U ore from White's, 6000 t Cu–U ore from Mount Burton, and about 10 000 t of custom ore were treated.
(b) White's, Dyson's, and Rum Jungle Creek South deposits only.
(c) Concentrate from Radium Hill was treated at Port Pirie, SA.
(d) Average grade of ore treated at Port Pirie; run-of-mine ore contained 0.09–0.13% U.
(e) Average grade of ore after radiometric ore sorting; run-of-mine ore contained 0.13% U.
(f) Excludes ore used to produce pitchblende concentrate and subsequently custom treated at Rum Jungle.
(g) Excludes ore used to produce pitchblende concentrate.
(h) In addition, UUNL supplied 150 t of pitchblende concentrate containing 70 t U to the Combined Development Agency (CDA).

Rum Jungle

Rum Jungle, the first Australian operation to produce uranium concentrates, began production in September 1954. The mine and plant were operated for the Commonwealth Government by Territory Enterprises Pty Ltd, a wholly owned subsidiary of Consolidated Zinc Pty Ltd (which, in 1962, merged with the Rio Tinto Mining Company of Australia Ltd to form Conzinc Rio Tinto of Australia Ltd, CRA). The Combined Development Agency (CDA) signed an agreement to purchase 1255 t U over a ten-year period on a cost-plus basis. Subsequent production was retained by the Australian Atomic Energy Commission on behalf of the Commonwealth. All mining operations were by open cut. The Rum Jungle plant was designed to produce about 150 t U/year from ore containing about 0.3% U. Sulphuric acid was used to leach the ore and, up to 1962, ion-exchange technology was used to separate the uranium, with magnesia being added to precipitate the yellowcake. From 1962, before the plant began treating ore from Rum Jungle Creek South, ion exchange was replaced by solvent extraction, and caustic soda was used to precipitate the uranium (Fitzgerald & Hartley, 1965; Warner, 1976; Alfredson, 1980). Production from the Rum Jungle treatment plant ended in 1971. Rehabilitation of the mine site and processing plant was carried out between 1982 and mid-1986, funded by the Commonwealth Government. The Northern Territory Government managed the work program. Monitoring of the site continued until 1988.

Radium Hill

Radium Hill was an underground mine operated by the South Australian Government to satisfy a cost-plus contract signed by the Commonwealth and South Australian Governments and the CDA, for delivery over seven years. The ore was concentrated at Radium Hill by heavy medium separation and flotation, to produce a concentrate containing about 0.7% U. The concentrate was transported to a treatment plant at Port Pirie designed to produce 136 t U/year. Approximately 346 t ore was mined from a deposit at Myponga (also known as Wild Dog deposit), 66 km south of Adelaide. According to Atomic Energy Commission file data this ore was treated at Port Pirie in 1957 and 1958 to produce 0.8 t U. It is not clear whether this production is included in the 721 t U attributed to Radium Hill in Table 2.

Mary Kathleen

Mary Kathleen was operated by Mary Kathleen Uranium Ltd as an open cut mine to supply 3460 t U (4080 t U_3O_8) to the UKAEA. Production of uranium oxide from the treatment plant began in June 1958, and by the end of 1963 the required amount of uranium in concentrates had been produced and the contract fulfilled. The mill had a nominal capacity of 760 t U/year. Before being finely ground, the ore was upgraded by radiometric sorting from 0.13% to 0.20% U. The treatment process used sulphuric acid to leach the ore, ion exchange to separate the uranium and then magnesia to precipitate the yellowcake. Upon completion of this contract in 1963 the mine, plant and township were placed on care-and-maintenance, to await opportunities for further sales. A second phase of production at Mary Kathleen commenced in 1976. This is discussed later in this chapter, under ‘Second phase’.

South Alligator Valley

United Uranium NL acquired an old gold treatment plant at Moline, some 65 km west-south-west of the South Alligator Valley uranium deposits, and converted the mill to treat uranium ore with a nominal capacity of 110 t U/year. The ore was leached by sulphuric acid, followed by solvent extraction of uranium and then magnesia precipitation to produce yellowcake (Warner, 1976). The company signed a contract to supply 441 t U to the UKAEA during 1959–66. The plant treated ore from nine small deposits and closed following completion of the contract in 1964.

South Alligator Uranium NL signed a contract with UKAEA for the delivery of 100 t U between 1958 and 1962. A small plant (nominal capacity 40 t U/year) was built near the company’s underground Rockhole mine. The plant used acid leaching of the ore, solvent extraction of the uranium, and magnesia to precipitate the yellowcake.

Second phase (1976 to the present)

Uranium production in Australia resumed in 1976; during this second phase, production has been from the Mary Kathleen, Nabarlek, Ranger, Olympic Dam and Beverley operations. From 1976 to the end of 2000, production from these operations totalled 83 425 t U (Table 3).

Mary Kathleen

A revival in world demand for uranium in the late 1960s enabled Mary Kathleen Uranium Ltd to secure new sales contracts. Production of uranium oxide concentrates from the mill resumed in 1976, but now solvent extraction was preferred to ion exchange because of lower operating costs. The mine was continued as an open cut. After producing enough uranium concentrates to satisfy existing contracts, the plant was closed in October 1982, because new contracts could not be secured at prices that would justify further production. Production from Mary Kathleen for this second period, from 1976 through to closure

Table 3. Second uranium production phase, 1976 to present (t U)*

Year	Mary Kathleen[(a)]	Nabarlek[(b)]	Ranger[(c)]	Olympic Dam[(d)]	Annual total[(e)]
1976	359	—	—	—	359
1977	356	—	—	—	356
1978	516	—	—	—	516
1979	706	—	—	—	706
1980	708	853	—	—	1 561
1981	699	1 209	952	—	2 860
1982	728	1 067	2 658	—	4 453
1983	—	1 029	2 188	—	3 218
1984	—	1 188	3 202	—	4 390
1985	—	1 115	2 136	—	3 252
1986	—	1 189	2 965	—	4 154
1987	—	1 148	2 631	—	3 780
1988	—	408	2 740	386	3 534
1989	—	—	2 790	867	3 657
1990	—	—	2 455	1 064	3 519
1991	—	—	2 646	1 113	3 759
1992	—	—	1 145	1 173	2 318
1993	—	—	1 132	1 106	2 238
1994	—	—	1 240	960	2 200
1995	—	—	2 550	1 150	3 700
1996	—	—	3 509	1 450	4 959
1997	—	—	4 063	1 416	5 479
1998	—	—	3 434	1 460	4 894
1999	—	—	3 271	2 713	5 984
2000	—	—	3 763	3 816	7 579
Totals[(e)]	4 072	9 208	51 471	18 674	83 425

Sources:
(a) MKU Ltd annual reports, production reports and press releases;
(b) Reports by Queensland Mines Ltd to Sydney Stock Exchange; after September 1981, Pioneer Concrete Services Ltd quarterly production reports to Sydney Stock Exchange;
(c) Energy Resources of Australia Ltd quarterly production reports to Sydney Stock Exchange;
(d) WMC (Olympic Dam Corporation) Ltd production reports to Commonwealth Government. Figures listed here are tonnes U produced at Olympic Dam. Quarterly and annual reports to shareholders by WMC Ltd give production in tonnes uranium ore concentrates. These concentrates assay slightly above 99% U_3O_8. Consequently, the U figures listed here are slightly smaller than the ore concentrate figures in company annual reports to shareholders.
(e) In some cases the total figure differs from the sum of the production figures from each mining operation, due to rounding errors.
*Production commenced at Beverley in November 2000, but the company reported nil production for the year.

in October 1982, was 4072 t U (4802 t U_3O_8) (Mary Kathleen Uranium Ltd, 1983). The remaining resource, of 1018 t U (1200 t U_3O_8) below the open cut, is unlikely ever to justify development (Mary Kathleen Uranium Ltd, 1981).

Rehabilitation of the mine and mill commenced in mid 1982. The mill and other surface plant and the township were dismantled and removed. The tailings dam was covered to a depth of 1 m with waste rock. Rehabilitation was completed by the end of 1984.

Nabarlek

Open cut mining at Nabarlek commenced in early June 1979 and the entire orebody was mined over a period of 4 months and 11 days. During this period, 2.33 Mt of overburden were removed, and 564 437 t ore and 157 000 t low grade mineralised rock were mined and stockpiled for treatment (Wilde & Noakes, 1990). The plant began operating in 1980, and sulphuric acid was used to leach the ore. Pyrolusite was originally used as the oxidant, but this was subsequently replaced by Caro's acid, to reduce the consumption of reagents (Lucas & others, 1983). Caro's acid is a mixture of hydrogen peroxide and sulphuric acid.

Uranium was separated by solvent extraction and precipitated by ammonia. The mill had a nominal capacity of 170 t ore/day to produce 915 t U/year, but annual production was often more than 1100 t U (Table 3). Processing of stockpiled ore was completed in 1988.

Rehabilitation of the minesite commenced in the late 1980s and was completed by the end of 1995. The mill was dismantled and most of the mill tailings and some of the waste rock were placed in the open cut, prior to final rehabilitation. Total production from the Nabarlek mill was 9208 t U (10 858 t U_3O_8).

Ranger

Development of the Ranger mine was the subject of the Ranger Uranium Environmental Inquiry, a major government inquiry under Justice Fox between 1975 and 1977 (Fox & others, 1976 & 1977). The findings of this inquiry allowed the development of both the Ranger and Nabarlek mines.

Open cut mining at the Ranger No. 1 Orebody began in August 1981 and was completed by December 1994. More than 5 Mt ore was stockpiled, providing mill feed for several years until open cut mining commenced at Ranger No. 3 Orebody in October 1996.

During the period from 1992 to 1994 inclusive, Energy Resources of Australia (ERA) Ltd reduced production from the Ranger operations to less than 1440 t U/year (1700 t U_3O_8). This reduction was in response to depressed market prices during this period, and was achieved by 'campaign mining and milling' whereby the process plant operated for six months from January to June each year and the mine operated from June to December. Additional uranium required to fulfil sales contracts during these years was purchased from the Republic of Kazakhstan.

By August 1997, the Ranger mill had been expanded from its previous capacity of 3000 t U/year (3500 t U_3O_8) to a nominal capacity of 4240 t U/year (5000 t U_3O_8), to generally coincide with the commencement of mining at No. 3 Orebody. The tonnages of ore processed increased from the previous level of 1.3 Mt/year to 2.0 Mt/year.

Since August 1997, the No. 1 Orebody open cut has been used as a repository for mill tailings. The company proposes to finally dispose of all mill tailings into the No. 1 and No. 3 Orebody open cuts, on completion of mining. Tailings that were previously deposited into the tailings dam were recovered using a dredge and pumped to the open cut for final disposal. Mining of No. 3 Orebody is expected to be completed in 2007, which will meet the requirement that No. 3 Orebody open cut be used as a tailings repository from 2008.

The mill uses a sulphuric acid leach process to dissolve uranium from the ore. Uranium is recovered from the leachate by solvent extraction and is precipitated as ammonium diuranate (yellowcake). This is then calcined to produce concentrates of uranium oxide (grey–green coloured powder) assaying more than 98.5% U_3O_8. In 1996, the mill was modified to use Caro's acid, which replaced pyrolusite as the oxidant in the leach process. The conversion to Caro's acid has resulted in improved metallurgical recoveries of uranium. Milling recoveries averaged 91% during the two-year period ended 30 June 2000.

Total production for Ranger, from the commencement of operations through to 31 December 2000, was 51 471 t U (60 697 t U_3O_8). In terms of annual production, Ranger was the world's third largest uranium mining company during 2000.

Jabiluka

An Environmental Impact Statement (EIS) for development of the Jabiluka deposit was submitted by Pancontinental Mining Ltd in July 1979. In 1982, the Northern Territory Government granted Pancontinental a mineral lease (MLN1) covering the deposit and adjacent areas for a period of 42 years. The mineral lease adjoins the Ranger Project Area, to the south, that includes the Ranger mine and mill operated by ERA Ltd.

An agreement was reached in 1982 with the Northern Land Council and Aboriginal traditional owners for mining to commence at Jabiluka. The election of the Commonwealth Labor Government in 1983 and the formulation of the 'Three mines' policy, restricting uranium mining to the Ranger, Nabarlek and Olympic Dam deposits, halted the development of the Jabiluka deposit. In 1991, ERA Ltd purchased the Jabiluka mineral lease from Pancontinental Mining Ltd, and previous agreements were transferred from Pancontinental to ERA.

Efforts to develop the Jabiluka deposit resumed when the 'Three mines' policy was removed by the Commonwealth Liberal–National Party Coalition Government, in 1996. In October 1996, ERA Ltd released a draft EIS for the project. It examined two milling options for the Jabiluka ore: in the Ranger Mill Alternative (RMA), the ore would be transported by truck to the existing Ranger mill for processing; in the Jabiluka Mill Alternative (JMA), the ore would be processed in a mill to be constructed on the Jabiluka lease (Kinhill, 1996).

The final EIS for the project was submitted to the Commonwealth and Northern Territory Governments in June 1997. In August 1997, the Commonwealth Environment Minister completed his assessment of the EIS and said that there did not appear to be any environmental issue that would prevent the preferred Jabiluka proposal (the RMA) from proceeding. The Minister required that stringent regulatory and operating conditions be applied to ensure the protection of World Heritage values, flora and fauna and cultural heritage (including Aboriginal sacred sites).

Subsequent to this approval, the Traditional Owners of the Jabiluka Mineral Lease area indicated that they were unwilling to consent to milling of Jabiluka ore at Ranger. In April 1998, the Commonwealth Environment Minister directed ERA to prepare a Public Environment Report to assist the Commonwealth and Northern Territory Governments in assessing the environmental impacts of the JMA. The Minister gave environmental clearances for the JMA in August 1998, on condition that all tailings be stored underground in the mine void. This would require the excavation of barren stopes for disposal of the tailings.

Construction of a decline (1150 m) and 720 m of underground drives and cross-cuts to access the orebody were completed by July 1999. Then ERA completed a program of underground diamond drilling and further environmental studies. A small tonnage of high-grade ore, mined from the cross-cuts through the orebody, was stockpiled at the surface.

In October 1999, the Northern Land Council, which negotiates on behalf of the Aboriginal Traditional Owners, advised ERA that it would not consider any proposal in relation to trucking ore from the Jabiluka mine to the Ranger mill until at least January 2005. The company subsequently reported that it would now focus on refining the best outcomes that can be delivered by developing a milling operation at Jabiluka.

Olympic Dam

Olympic Dam is a large-scale underground mining operation using long-hole open stoping methods. Development of the project started in December 1985, and production commenced in August 1988. Initially, 2.2 Mt ore was treated annually to produce 1400 t U_3O_8 (1190 t U) as well as 65 000 t refined copper, and associated refined gold and silver. Up to 1993, the project was a joint venture between WMC Ltd and BP Minerals.

In 1993, WMC Ltd acquired full ownership of Olympic Dam. The mine and processing facilities are now operated by WMC (Olympic Dam Corporation) Pty Ltd, a wholly owned subsidiary of WMC Ltd.

Between 1989 and 1995, the annual capacity of the processing plant was increased in two stages to 85 000 t copper and 1700 t U_3O_8 (1440 t U) plus associated gold and silver from the processing of 3.0 Mt ore/year. A major expansion of the project was completed in March 1999 at a cost of A$1.94 billion. Annual production capacity was increased to 200 000 t copper, 4600 t U_3O_8 (3900 t U), 2050 kg gold and 23 000 kg silver. To sustain this rate of production, approximately 8.7–9.2 Mt ore are mined and processed annually (Kinhill, 1997). Water required for mining and processing operations and for the township of Roxby Downs is pumped from borefields within the Great Artesian Basin. The main borefield is located more than 175 km north-east of the mine.

The major expansion was granted approval only after a comprehensive EIS had been assessed by the Commonwealth and South Australian Governments. The company was also required to augment the existing environmental controls on the project with additional conditions relating to the management of the Great Artesian Basin water resources, future assessments of the tailing management system, and impacts of future changes to technology and mining practices.

Further expansions of the project to 350 000 t copper and approximately 7700 t U_3O_8 (6500 t U) are being investigated by the company.

The metallurgical plant recovers copper, uranium, gold and silver. Briefly, the uranium recovery process is as follows. After crushing and grinding, the ore is mixed with water and the slurry is pumped to the flotation plant. Copper concentrates are produced using standard flotation processes. The non-sulphide particles, which do not float (referred to as flotation tailings), contain most of the uranium minerals. Acid mixed with an oxidant is then added to leach uranium from the flotation tailings, and the slurry is heated to 60°C to improve the leach process. Uranium is recovered from the leach liquor by solvent extraction. Pulsed column technology is used to improve the recovery rate and to reduce the consumption of organic reagents. The solutions containing dissolved uranium are treated with ammonia to precipitate ammonium diuranate (yellowcake), which is then calcined to produce uranium oxide, a dark grey–green powder that assays slightly higher than 99% U_3O_8.

Total production from the Olympic Dam operation from the start of production through to the end of 2000 was 18 674 t U (22 021 t U_3O_8).

Beverley

The Beverley project is Australia's first commercial in situ leach uranium mining operation. Uranium in the host sandstone is leached in situ using sulphuric acid and an oxidant, hydrogen peroxide, and then the leachates containing dissolved uranium are pumped to the surface via production wells. Uranium is recovered in the process plant using ion-exchange technology. The chemistry of the acid leach process and the ion-exchange technology are described later, in the 'Beverley deposit' section of the 'Sandstone deposits' chapter. The process plant has a nominal capacity of 848 t U/year (1000 t U_3O_8).

Kintyre

In 1996, Canning Resources advised the Commonwealth and Western Australian Governments of its intention to develop the Kintyre deposit, and work commenced on the environmental impact assessment of the proposed mining operation. The operation planned to produce 1200 t/year (tpa) U_3O_8, with the potential to increase production up to 2000 tpa U_3O_8 over a twenty-year period. The company proposed to mine each of the orebodies using separate open pits. Before being milled, the ore was to be upgraded by radiometric sorting and the smaller size fraction was to be concentrated using ferrosilicon heavy-medium separation. Uranium was to be extracted using an acid leach process (Canning Resources, 1996). However, the company decided in 1997 to delay the development of the deposit because of the low uranium prices at that time.

Overall

Australia's uranium production for 2000 was 22% of world production, and Australia ranked as the second largest producer. Canada maintained its position as the world's largest producer, with 31% of world production (Table 4).

Although Australia has the world's largest resources in the Reasonably Assured Resources category recoverable at ≤US$80/kg U, Australia's cumulative production to the end of 2000 (91 157 t U) represents less than 4.7% of world cumulative production to the end of 2000 (Table 4). The major producing countries have been USA, Canada, Germany, South Africa, Russian Federation and Czech Republic.

Table 4. Historical production of mined uranium, by country (t U)

	pre-1997	1997	1998	1999	2000	Total to end of 2000
Australia	67 221	5 479	4 894	5 984	7 579	91 157
Canada	298 673	12 031	10 922	7 896	10 682	340 204
Czech Republic[(a)]	104 748	603	610	313	323	106 597
France	72 903	572	507	439	319	74 740
Germany[(b)]	218 727	28	30	30	28	218 843
Kazakhstan	82 582	1 090	1 270	1 367	1 771	88 080
Namibia	61 037	2 905	2 780	2 689	2 715	72 126
Niger	68 785	3 487	3 714	2 918	2 898	81 802
Russian Federation	103 983	2 580	2 530	1 500	1 500	112 093
South Africa	149 507	1 100	994	981	817	153 399
Ukraine[(c)]	n.a.	1 000	1 000	1 200	1 200	>5 400
United States	346 518	2 170	1 810	1 871	1 493	353 862
Uzbekistan	87 881	1 764	1 926	2 130	2 010	95 711
Others[(d)]	>128 095	1 906	1 983	1 486	1 351	>134 821
TOTAL[(e)]	>1 791 660	36 715	34 970	30 804	34 686	>1 928 835

Source: Production data for all years except 1999 and 2000 are from OECD/NEA & IAEA (2000); data for 1999 and 2000 are from NUKEM Market Report April 2001; data for Australia are as for Tables 2 & 3.
(a) Includes production from the former Czech and Slovak Federal Republic.
(b) Includes production from the former German Democratic Republic.

(c) Pre-1996 production figures not available for Ukraine.
(d) Argentina, Belgium, Brazil, Bulgaria, China, Finland, Gabon, Hungary, India, Japan, Mexico, Mongolia, Pakistan, Poland, Portugal, Romania, Slovenia, Spain, Sweden, Yugoslavia, Zaire.
(e) Total production was greater than the amount shown because pre-1997 production figures for Ukraine and China are not available.
n.a. not available.

IDENTIFIED RESOURCES

Classification of uranium resources

Geoscience Australia prepares annual estimates of Australia's uranium resources within categories defined by the OECD Nuclear Energy Agency (OECD/NEA) and the International Atomic Energy Agency (IAEA). It releases these estimates in an annual publication entitled *Australia's Identified Mineral Resources*. Table 5 shows the estimates for December 2000.

Table 5. Recoverable uranium resources (t U), December 2000, reported according to NEA/IAEA resource classification scheme

	Reasonably Assured Resources Cost ranges[d]			Estimated Additional Resources — Category I Cost ranges[d]		
	≤US$40/kg U (≤US$15/lb U_3O_8)	≤US$80/kg U (≤US$30/lb U_3O_8)	≤US$130/kg U (≤US$50/lb U_3O_8)	≤US$40/kg U (≤US$15/lb U_3O_8)	≤US$80/kg U (≤US$30/lb U_3O_8)	≤US$130/kg U (≤US$50/lb U_3O_8)
Australia	654 000	667 000	697 000	185 000	196 000	233 000
Brazil[a]	56 100	162 000	162 000	NA	100 200	100 200
Canada	284 560	326 420	326 420	87 010	106 590	106 590
France	NA	12 460	14 240	NA	550	550
Gabon	4 830	4 830	4 830	1 000	1 000	1 000
Kazakhstan[a]	320 740	436 620	598 660	113 200	195 600	259 300
Mongolia[a]	10 600	61 600	61 600	11 000	21 000	21 000
Namibia	67 240	149 270	180 510	70 550	90 820	107 510
Niger	43 590	71 120	71 120	0	0	18 580
Russian Fed.[a]	64 300	140 900	140 900	17 200	36 500	36 500
South Africa	121 000	232 900	292 800	48 100	66 800	76 400
Ukraine[a]	–	42 600	81 000	–	20 000	50 000
USA	NA	106 000	355 000	–	–	–
Uzbekistan	65 620	65 620	83 090	39 850	39 850	46 990
Other countries[b]	5 860	95 970	117 830	4 230	27 640	131 810
Total	> 1 698 440	2 575 310	3 247 000	> 577 140	902 550	1 189 430
Total adjusted[c]	> 1 570 000	2 334 000	2 945 000	> 523 000	777 000	1 029 000

Sources: Data for Australia compiled by Geoscience Australia as at December 2000. Estimates for all other countries are from OECD/NEA & IAEA (2000).

(a) In situ resources with no allowances for mining and milling losses.

(b) Algeria, Argentina, Bulgaria, Central African Republic, Czech Republic, Greece, Italy, Islamic Republic of Iran, Mexico, Slovenia, Somalia, Spain, Sweden, Zaire, Zimbabwe.

(c) Totals have been adjusted by OECD/NEA and IAEA to account for milling and/or mining losses not incorporated in the estimates for Brazil, Kazakhstan, Mongolia, Russian Federation, Ukraine and certain countries grouped under 'Other Countries'.

(d) Resources in ≤US$80 category include those resources in ≤US40 category. Resources in ≤US$130 category include those resources in ≤US$80 category.

The OECD/NEA and the IAEA prepare periodical updates (usually every two years) of world uranium resources. These updates are published in *Uranium Resources, Production and Demand*, commonly known as the 'Red Book'. The latest edition (OECD/NEA & IAEA, 2000) gives resources data as at 1 January 1999. National agencies from each country provide estimates of uranium resources and other data in response to questionnaires distributed by the NEA/IAEA Uranium Group. For the NEA/IAEA classification scheme, resource estimates are divided into the following categories (defined in Appendix 1) that reflect the level of confidence in the quantities reported:

- Reasonably Assured Resources (RAR),
- Estimated Additional Resources — Category I (EAR-I),
- Estimated Additional Resources — Category II (EAR-II),
- Speculative Resources.

The resources are further separated into categories based on the cost of production: ≤US$40/kg U; ≤US$80/kg U; and ≤US$130/kg U.

All the estimates of resources are expressed in terms of tonnes (t) of recoverable uranium (U) rather than uranium oxide (U_3O_8). Estimates refer to quantities of uranium recoverable from mineable ore, i.e. the estimates include allowances for ore dilution, mining and milling losses.

The NEA/IAEA classification, which has been adopted internationally for uranium resources, can be broadly equated with the national classification scheme that Geoscience Australia uses for other minerals. For example, RAR at ≤US$40/kg U approximates Economic Demonstrated Resources; RAR in the US$40–80/kg U category approximates Paramarginal Demonstrated Resources; RAR in the US$80–130/kg U category approximates Submarginal Demonstrated Resources; EAR-I is equivalent to Inferred Resources. The NEA/IAEA classification differs from the national scheme in that it quantifies the cost of production of resources.

Resource estimates within the various categories change with shifts in economic conditions and with progress in exploration and technology. Local production costs may be altered by inflation or variations in exchange rates, causing the cost of recovering uranium in certain deposits to cross the boundary between two cost classifications; then the estimates have to be revised. As exploration proceeds there is a movement of resources from EAR-I to RAR, and as production proceeds there is a corresponding reduction in RAR. Furthermore, improvements in technology can lead to revisions in the recoveries and consequent alteration in resource estimates.

Estimates of Australia's total resources within the various categories are aggregated from estimates for individual deposits by companies (as published in annual reports) and by Geoscience Australia using basic exploration data provided by companies in accordance with the *Atomic Energy Act 1953*. Australia's resources are estimated for RAR and EAR-I within the cost categories ≤US$40/kg U, ≤US$80/kg U and ≤US$130/kg U (Table 5). The ≤US$40 category was introduced into the NEA/IAEA scheme to reflect a production cost range that is more relevant to uranium market prices that prevailed during the late 1990s and 2000.

Approximately 95% of Australia's total uranium resources in RAR recoverable at ≤US$80/kg U are within the following six deposits (Fig. 1):

- Olympic Dam (SA), which is the world's largest uranium deposit,
- Ranger, Jabiluka, Koongarra in the Alligator Rivers region (NT),
- Kintyre and Yeelirrie (WA).

World ranking of uranium resources

Australia's resources in RAR recoverable at ≤US$40/kg U are more than any other country has reported, to date, in this category. Australia has the largest resources of uranium in RAR recoverable at ≤US$80/kg U, with 29% of world resources in this category (Fig. 3). Other countries that have large resources in this category include Kazakhstan (19%), Canada (14%), South Africa (10%), Brazil (7%), Namibia (6%), Russian Federation (6%) and United States (5%).

The latest reserve/resource estimates reported by the mining companies for Australian deposits are recorded in Table 6 and Fig. 4, by deposit type (described in the next chapter). The estimates that are based on recent data are shown in the JORC Code categories (JORC, 1999); estimates based on earlier data are in the categories stated by the companies.

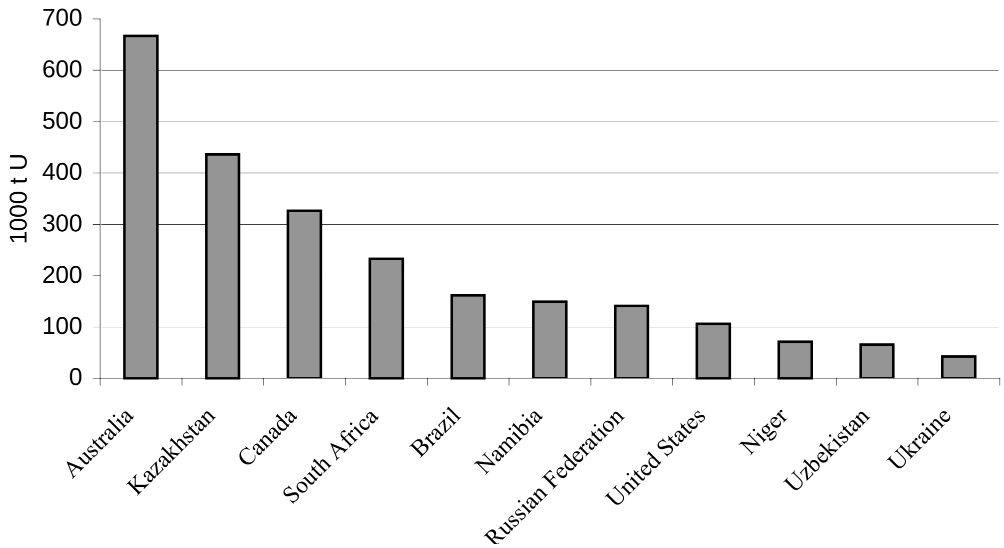

Figure 3. Reasonably Assured Resources of uranium recoverable at ≤US$80/kg U in major resource countries

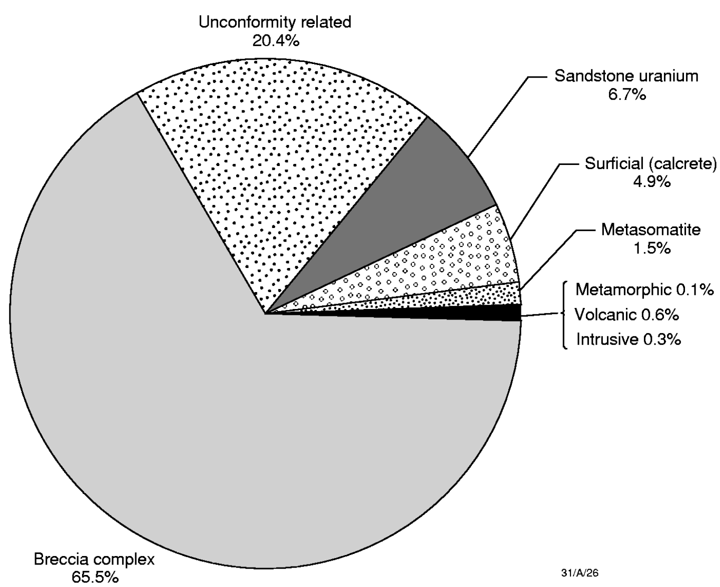

Figure 4. Distribution of Australia's uranium resources within deposit types

Estimates of the initial global resources for Australian deposits are given in Table 7. Where estimates for a particular deposit are available at several cut-off grades, the estimate given is for the lowest cut-off, which reflected the economic conditions at the time of the estimation. See also Appendix 2 for a list of Australia's uranium deposits and significant prospects, by name, and Appendix 3 for details of the ownership of uranium mines and major deposits as at July 2000.

Table 6. Resources and grades of Australia's uranium deposits as at December 2000 (resource estimates as published by companies)

Deposit	U_3O_8 tonnes	Grade % U_3O_8	Cut-off % U_3O_8	Resource category [a]	Company
BRECCIA COMPLEX DEPOSITS					
Stuart Shelf area of Gawler Craton					
Olympic Dam	280 000	0.05		Measured resources (includes Proved Reserves)	Western Mining Corp. Ltd
	524 000	0.04		Indicated resources (includes Probable Reserves)	
	192 000	0.03		Inferred resources	
Mount Painter field					
Radium Ridge	2 177	0.06	0.05	In situ	Exoil NL
Mount Gee	2 722	0.10	0.05	In situ	Exoil NL
Armchair–Streitberg	1 814	0.10	0.05	In situ	Exoil NL
Hodgkinson	567	0.25	0.05	In situ	Exoil NL
Sub–total [d]	*1 003 280*				
	65.5%				
UNCONFORMITY-RELATED DEPOSITS					
Alligator Rivers uranium field					
Ranger No.1 Orebody	0			Mined out	Energy Resources of Aust. Ltd
Ranger No.3 Orebody	57 000	0.26	0.12	Measured plus indic. resources [b]	Energy Resources of Aust. Ltd
	23 251	0.26	0.12	Inferred resources	Energy Resources of Aust. Ltd
Jabiluka 1 Orebody	3 400	0.25	0.05	Geological resource	Energy Resources of Aust. Ltd
Jabiluka 2 Orebody	88 000	0.57	0.2	Measured plus indic. resources [b,c]	Energy Resources of Aust. Ltd
	75 000	0.48	0.2	Inferred resources	
Koongarra 1 Orebody	14 500	0.8		Proved and probable reserves	Cogema Australia Pty Ltd
Koongarra 2 Orebody	2 000	0.3		Unspecified	
Nabarlek	0			Mined out	Queensland Mines Pty Ltd
Ranger 68	5 000	0.357	0.1	'Resources'	
Hades Flat	726			Unspecified	
Caramal	2 500			'Resources'	
Rum Jungle field					
Mount Fitch	1 500	0.042		In situ	
South Alligator Valley field					
Coronation Hill	1 850	0.537		Indicated resources	
Pine Creek Inlier					
Adelaide River	8	0.5		Stockpile	
	12	0.22		Possible resources	
Twin	304	0.12		Measured plus indicated resources	Total Mining Australia Pty Ltd
Dam	442	0.13		Measured plus indicated resources	Total Mining Australia Pty Ltd
Rudall Province					
Kintyre	24 500	0.15–0.4		Probable resources	Canning Resources Pty Ltd
	11 500	0.15–0.4		Inferred resources	(subsidiary of Rio Tinto Ltd)
Turee Creek Area					
Angelo River 'A'	797	0.124		'Mineralisation'	
Sub-total [d]	*312 290*				
	20.4%				

Table 6 continued

SANDSTONE DEPOSITS					
Lake Eyre Basin — Frome Embayment					
Beverley	10 600			Total resources recoverable by ISL[f]	Heathgate Resources Pty Ltd
Honeymoon	3 900			Total resources recoverable by ISL	Southern Cross Resources Inc.
East Kalkaroo	4 000			Total resources recoverable by ISL	Southern Cross Resources Inc.
Goulds Dam	17 600			Total resources recoverable by ISL	Southern Cross Resources Inc.
Eucla Basin					
Warrior	4 000	0.034			PNC Exploration (Aust.) Pty Ltd
McArthur Basin — Westmoreland area					
Redtree	12 600	0.126		Inferred resources	Rio Tinto Exploration Pty Ltd
Junnagunna	5 300	0.098		Inferred resources	Rio Tinto Exploration Pty Ltd
Huarabagoo	3 000	0.169		Inferred resources	Rio Tinto Exploration Pty Ltd
Sue	675	0.16		'Resources'	Rio Tinto Exploration Pty Ltd
Outcamp	945	0.16		'Resources'	Rio Tinto Exploration Pty Ltd
Amadeus Basin					
Angela	4 700	0.13	0.05	Measured resources	Palladin Resources Ltd
	1 950	0.1	0.05	Indicated resources	
	>3 600	0.1	0.05	Inferred resources	
Ngalia Basin					
Bigrlyi	2 181	0.372		Proved resources	Central Pacific Minerals NL, and other partners
	486	0.252		Probable resources	
	107	0.361		Possible resources	
Walbiri	686	0.162		Resources	Central Pacific Minerals NL, and other partners
Gunbarrel Basin					
Mulga Rock deposits	15 330	0.14	0.035	'Total resources'	PNC Exploration (Australia) P/L
Carnarvon Basin					
Manyingee	5 000			Total resources recoverable by ISL	Cogema Australia Pty Ltd
Bennetts Well	1 500	0.16		Total resources	Eagle Bay Resources NL
Canning Basin					
Oobagooma	5 000			Total resources recoverable by ISL	Cogema Australia Pty Ltd
Sub-total [d]	*103 160* *6.7%*				
SURFICIAL (CALCRETE) DEPOSITS					
Yilgarn Craton					
Yeelirrie	52 500	0.15		Proved ore reserves	Western Mining Corp. Ltd
Lake Way	3 300		0.065	Reserves	Wiluna Mines Ltd
Lake Maitland	5 016	0.07	0.05	Indicated and inferred resources	Acclaim Uranium NL
Centipede	3 800	0.1		Category not reported	Wiluna Mines Ltd
Abercrombie				Included in Centipede resources	Acclaim Uranium NL
Millipede				Included in Centipede resources	Acclaim Uranium NL
Nowthanna	2 023	0.086	0.05	Indicated resources	Acclaim Uranium NL
Thatcher Soak	4 100	0.03			Cultus Pacific NL
Lake Mason	2 700	0.035			Cultus Pacific NL
Lake Raeside	1 700	0.025	0.02		
Sub-total [d]	*75 139* *4.9%*				

Table 6 continued

METASOMATITE DEPOSITS					
Valhalla	6 024	0.15	0.08	Measured resources	Summit Resources NL
	6 880	0.144	0.08	Indicated resources	
	3 627	0.135	0.08	Inferred resources	
Skal	3 450	0.13	0.05	Identified mineral resources	Summit Resources NL
Anderson's Lode	2 100	0.167			Summit Resources NL
Sub-total [(d)]	*22 081*				
	1.5%				
METAMORPHIC DEPOSITS					
Mary Kathleen	1 200			Resources below base of open cut	Mary Kathleen Uranium Ltd
Elaine	100	0.06		In situ resources	Mary Kathleen Uranium Ltd
Sub-total [(d)]	*1 300*				
	0.1%				
VOLCANIC DEPOSITS					
Ben Lomond	4 758	0.246	0.12 [(e)]	Mineable ore reserves	Cogema Australia P/L
Maureen	2 940	0.123		Total proved and probable resources	Central Coast Exploration NL
Twogee	755	0.12		Resources	Minatome Australia Pty Ltd
Trident	495	0.22		In situ resources	Minatome Australia Pty Ltd
Sub-total [(d)]	*8 948*				
	0.6%				
INTRUSIVE DEPOSITS					
Olary field					
Mount Victoria	198	0.3		Mineable reserves	North Flinders Mines Ltd
Crocker Well	5 000	0.05		In situ resources	
Sub-total [(d)]	*5 198*				
	0.3%				
VEIN DEPOSITS					
	Nil				
Grand total	*1 531 396*				
	100%				

(a) Resource classification and the categories used are those applicable at the time when the various deposits were calculated. The earlier classification schemes used for some deposits do not conform to the 1999 Edition of the Australasian Code for Reporting of Mineral Resources and Ore Reserves (JORC Code, 1999). These resource categories also differ from the NEA/IAEA resource classification scheme.
(b) Source: ERA Ltd Annual Report 2000.
(c) Includes proved plus probable reserves of 71 000 t U_3O_8 averaging 0.51% U_3O_8.
(d) Sub-totals for the resources in this table give a broad indication of the relative importance of different uranium deposit types in Australia. The sub-totals are not meant to conform to the Australasian Code for Reporting for Mineral Resources and Ore Reserves 1999 Edition (The JORC Code).
(e) Cut off grade of 0.12% U_3O_8 for proposed open cut and 0.16% U_3O_8 for proposed underground mine.
(f) ISL stands for in situ leach mining.

Table 7. Initial global resources (includes past production) of Australia's uranium deposits (resource estimates as published by companies)

Deposit	U_3O_8 tonnes	Grade % U_3O_8	Cut-off % U_3O_8	Comments	Company
BRECCIA COMPLEX DEPOSITS					
Stuart Shelf area of Gawler Craton					
Olympic Dam	1 018 022			Resources at 31/12/00 plus past production	Western Mining Corp. Ltd
Mount Painter field					
Radium Ridge	2 177	0.06	0.05	Resources	Exoil NL
Mount Gee	2 722	0.10	0.05	Resources	Exoil NL
Armchair-Streitberg	1 814	0.10	0.05	Resources	Exoil NL
Hodgkinson	567	0.25	0.05	Resources	Exoil NL
Sub-total [(b)]	*1 025 302* *60.3%*				
UNCONFORMITY-RELATED DEPOSITS					
Alligator Rivers Uranium Field					
Ranger No.1 Orebody	57 392	0.259	0.05	Mined out – Initial in situ resource	Energy Resources of Aust. Ltd
Ranger No.3 Orebody[(a)]	85 051	0.20	0.05	Probable plus possible resources	Energy Resources of Aust. Ltd
Jabiluka 1 Orebody	3 400	0.25	0.05	Geological resource	Pancontinental Mining Ltd
Jabiluka 2 Orebody	204 000	0.39	0.05	Initial in situ resource	Pancontinental Mining Ltd
Koongarra 1 Orebody	14 500	0.8		Proved and probable reserves	Cogema Australia Pty Ltd
Koongarra 2 Orebody	2 000	0.3		Total resources	
Nabarlek	10 858			Mined out – total production from deposit.	
Ranger 68	5 000	0.357	0.1	'Resources'	
Hades Flat	726			Resources	
Caramal	2 500			Resources	
Rum Jungle field					
Dyson's	534	0.34		Production	
White's	1 088	0.27		Ditto	
Mount Burton	13	0.21		Ditto	
Rum Jungle Creek South	2 860	0.43		Ditto	
Mount Fitch	1 500	0.042		In situ resources	
South Alligator Valley field					
Coronation Hill	1 925	0.537		Indicated resources plus past production of 75 t U_3O_8	
El Sherana	226	0.55		Production	
El Sherana West	185	0.82		Ditto	
Palette	124	2.45		Ditto	
Other small deposits	264	0.76		10 other small deposits — production from individual deposits ranges from 3 to 78 t U_3O_8	
Pine Creek Inlier					
Adelaide River	39	0.5		Resources plus production	
Fleur de Lys	0.1	0.12		Total production	
George Creek	0.3	0.22		Total production	
Twin	304	0.12		Measured plus indicated resources	Total Mining Australia Pty Ltd
Dam	442	0.13		Measured plus indicated resources	Total Mining Australia Pty Ltd
Rudall Province					
Kintyre	36 000	0.15–0.4		Total resources	Canning Resources Pty Ltd (subsidiary of Rio Tinto Ltd)
Turee Creek Area					
Angelo River 'A'	797	0.124		'Mineralisation'	
Sub-total [(b)]	*431 728* *25.4%*				

Table 7 continued

SANDSTONE DEPOSITS					
Lake Eyre Basin — Frome Embayment					
Beverley	16 300			Total resources	Heathgate Resources Pty Ltd
Honeymoon	3 900			Total resources	Southern Cross Resources Inc.
East Kalkaroo	4 000			Total resources	Southern Cross Resources Inc.
Goulds Dam	17 600			Total resources	Southern Cross Resources Inc.
Eucla Basin					
Warrior	4 000	0.034			PNC Exploration (Aust.) Pty Ltd
McArthur Basin — Westmoreland area					
Redtree	12 600	0.126		Inferred resources	Rio Tinto Exploration Pty Ltd
Junnagunna	5 300	0.098		Inferred resources	Rio Tinto Exploration Pty Ltd
Huarabagoo	3 000	0.169		Inferred resources	Rio Tinto Exploration Pty Ltd
Sue	675	0.16		'Resources'	Rio Tinto Exploration Pty Ltd
Outcamp	945	0.16		'Resources'	Rio Tinto Exploration Pty Ltd
Amadeus Basin					
Angela	10 250	0.11	0.05	Total resources	Palladin Resources Ltd
Ngalia Basin					
Bigrlyi	2 774	0.35		Total resources	Central Pacific Minerals NL, and other partners
Walbiri	686	0.162		Total resources	Central Pacific Minerals NL, and other partners
Gunbarrel Basin					
Mulga Rock deposits	15 330	0.14	0.035	Total resources	PNC Exploration (Australia) P/L
Carnarvon Basin					
Manyingee	7 000			Total resources	Cogema Australia Pty Ltd
Bennetts Well	1 500	0.16		Total resources	Eagle Bay Resources NL
Canning Basin					
Oobagooma	10 000	0.12		Total resources	Cogema Australia Pty Ltd
Sub-total [(b)]	*115 860* *6.8%*				
SURFICIAL (CALCRETE) DEPOSITS					
Yilgarn Craton					
Yeelirrie	52 500	0.15		Proved ore reserves	Western Mining Corp. Ltd
Lake Way	3 300		0.065	Reserves	Wiluna Mines Ltd
Lake Maitland	5 016	0.07	0.05	Indicated and inferred resources	Acclaim Uranium NL
Centipede	3 800	0.1		Category not reported	Wiluna Mines Ltd
Abercrombie				Included in Centipede resources	Acclaim Uranium NL
Millipede				Included in Centipede resources	Acclaim Uranium NL
Nowthana	2 023	0.086	0.05	Indicated resources	Acclaim Uranium NL
Thatcher Soak	4 100	0.03			Cultus Pacific NL
Lake Mason	2 700	0.035			Cultus Pacific NL
Lake Raeside	1 700	0.025	0.02		
Sub-total [(b)]	*75 139* *4.4%*				
METASOMATITE DEPOSITS					
Valhalla	16 531	0.14	0.08	Total resources	Summit Resources NL
Skal	3 450	0.13	0.05	Identified mineral resources	Summit Resources NL
Anderson's Lode	2 100	0.167			Summit Resources NL
Sub-total [(b)]	*22 081* *1.3%*				

Table 7 continued

METAMORPHIC DEPOSITS				
Mary Kathleen	12 000	0.131	Initial total resources	Mary Kathleen Uranium Ltd
Elaine	100	0.06	In situ resources	Mary Kathleen Uranium Ltd
Sub-total	*12 100* *0.7%*			
VOLCANIC DEPOSITS				
Ben Lomond	6 792	0.228	Total resources	Cogema Australia P/L
Maureen	2 940	0.123	Total proved and probable resources	Central Coast Exploration NL
Twogee	755	0.12	Resources	Minatome Australia Pty Ltd
Trident	495	0.22	In situ resources	Minatome Australia Pty Ltd
Sub-total (b)	*10 982* *0.7%*			
INTRUSIVE DEPOSITS				
Olary field				
Radium Hill	850	0.70–0.90	Total production	
Mount Victoria	198	0.3	Mineable reserves	North Flinders Mines Ltd
Crocker Well	5 000	0.05	In situ resources	
Sub-total (b)	*6 048* *0.4%*			
VEIN DEPOSITS	Nil			
Grand total	*1 699 240* *100%*			

(a) Source: ERA Ltd Annual Report 1986

(b) Subtotals in this table provide a general indication of the distribution of Australia's uranium resources/reserves/mineralisation in various uranium deposit types.

TYPES OF URANIUM DEPOSITS

The OECD/NEA and IAEA (2000) have classified uranium deposits worldwide into fifteen deposit types on the basis of their geological setting. They are listed below in the order of their approximate economic significance in Australia, and then their main features are described. The approximate economic significance worldwide of the seven most important types is shown in brackets.

- breccia complex deposits; (3)
- unconformity-related deposits; (1)
- sandstone deposits; (2)
- surficial deposits; (6)
- metasomatite deposits; (7)
- metamorphic deposits;
- volcanic deposits;
- intrusive deposits; (5)
- vein deposits;
- quartz-pebble conglomerate deposits; (4)
- collapse breccia pipe deposits;
- phosphorite deposits;
- lignite;
- black shale deposits;
- other types of deposits.

Breccia complex deposits

The Olympic Dam deposit is the only known breccia complex deposit that has significant resources of uranium. Several iron-rich breccia deposits (with varying amounts of uranium, copper and rare earth elements) in the Gawler Craton and in the Mount Painter area (SA) are similar to Olympic Dam.

The Olympic Dam deposit occurs in a hematite-rich granite breccia complex in the Gawler Craton. It is overlain by approximately 300 m of flat-lying sedimentary rocks of the Stuart Shelf geological province. The breccia complex is associated with a Mesoproterozoic plutonic intrusion and co-magmatic continental felsic volcanics. The intrusion, volcanics and breccia complex developed in a post-orogenic tectonic setting.

The breccia complex is entirely within the granite intrusion, and consists of a variety of breccia types ranging from granite-rich breccias, through hematitic granite breccias, to hematite-rich breccias.

There is a broad zonal distribution of the major rock types within the breccia complex. The central core of the complex is barren hematite-quartz breccias, with several localised diatreme structures (see Figs 7 and 8 in the next chapter). The hematite-quartz core is flanked to the east and west by zones of intermingled hematite-rich breccias and altered granitic breccias. These zones are approximately 1 km wide and extend almost 5 km in a north-west–south-east direction. Virtually all the economic copper–uranium mineralisation is hosted by hematite-rich breccias (Reeve & others, 1990). This broad zone is surrounded by granitic breccias extending up to 3 km beyond the outer limits of the hematite-rich breccias. The outer limits of the breccia complex are gradational with the Roxby Downs Granite.

The breccias and mineralisation were formed by hydrothermal processes. Much of the brecciation occurred in the near surface eruptive environment of a crater complex during eruptions caused by boiling and explosive interaction of water (from lake, sea or groundwater) with magma (Reeve & others, 1990).

On the basis of geological evidence, Reeve and others (1990) argue that the hydrothermal activity which formed the breccia complex occurred in the time between intrusion of the Roxby Downs Granite (~1590 Ma) and cessation of Gawler Range Volcanic activity (~1575 Ma). The results of U–Pb isotopic age dating (Creaser & Cooper, 1993; Johnson & Cross, 1995) together with geological evidence (Reeve & others, 1990) suggest that introduction and deposition of ore metals occurred at the same time as the formation of the hematite breccias. For rocks within the breccia complex and the diatreme, U–Pb zircon dates indicate that the breccia complex formed at ~1590 Ma, and that brecciation closely followed emplacement and cooling of the Roxby Downs Granite (Johnson & Cross, 1995).

The Olympic Dam copper–uranium–gold deposit has the world's largest resource of low-cost uranium. As at December 2000, the total uranium reserves plus resources accounted for approximately 65% of Australia's reserves plus resources (Table 6). Together with past production of 22 022 t U_3O_8 to December 2000, the total initial global uranium resources amounted to about 2547 Mt containing an estimated 1 018 022 t U_3O_8 (Table 7). The deposit is also a major copper and gold producer. Silver is another important co-product and the deposit has significant amounts of rare earth elements (lanthanum and cerium), and has an iron content of about 26% Fe. The overall grades of the resource are about 1.3% Cu, 0.4 g/t Au and 2.9 g/t Ag.

In addition to Olympic Dam, the Gawler Craton hosts a number of less richly mineralised iron oxide deposits including Acropolis, Wirrda Well, Oak Dam, Emmie Bluff and Murdie. Depending upon the degree of brecciation, hematite:magnetite ratios, and the extent and grade of uranium, copper, gold, silver and rare earth elements (REE) mineralisation, these deposits form a spectrum of styles of mineralisation (Gow & others, 1994; Hitzman, 2000). The Olympic Dam deposit belongs to the mineralised hematite-rich end of the spectrum, whereas the Murdie deposit is at the magnetite-rich poorly mineralised end of the spectrum.

In the Mount Painter area, 270 km east of Olympic Dam, a number of small uranium–rare earth element deposits occur within hematite-rich granitic breccias. The largest of these is the Mount Gee deposit which has 2722 t U_3O_8 and an average grade of 0.1% U_3O_8. Recent drilling has identified a large body of low-grade uranium–REE–copper mineralisation in hematite breccias at the Mount Gee East prospect. These deposits in the Mount Painter area are considered to be breccia-complex-type deposits (Drexel & Major, 1987). Drexel and Major (1990) and Lambert and others (1982) considered these to be hydrothermal breccias associated with intrusion of Palaeozoic granites. They proposed a late Ordovician to Silurian age for the hydrothermal activity and mineralisation. Later, Idnurm and Heinrich (1993) proposed a Permo-Carboniferous age for the hydrothermal activity and the uranium mineralisation, on the basis of a palaeomagnetic study. However, they stated that an older age of the mineralisation could not be excluded. More recent work by Neumann and others (2000) noted that extreme enrichment of U, Th and K in Mount Painter Granite (dated at 1575 and 1555 Ma) could be a primary feature. The relationship, if any, of this possible primary mineralisation to uranium breccias is not known.

At the time of its discovery in 1975, the Olympic Dam deposit was considered to be a unique type of iron-rich copper–uranium–gold–silver deposit. Since its discovery, some researchers have drawn comparisons between Olympic Dam and a group of large Proterozoic iron-rich deposits (Hitzman, Oreskes & Einaudi, 1992). Examples of such iron-rich deposits include the Kiruna iron ore deposits, Sweden; iron ore deposits of south east Missouri, USA; Wernecke Mountain breccia deposits, Yukon; and Sue–Dianne copper deposit in the Northwest Territories, Canada. More recently, the Olympic Dam deposit has been assigned to a broad suite of loosely related iron oxide–copper–gold deposits ranging in age from ?2570 to 1000 Ma that include Ernest Henry (1480 Ma), Starra (1500 Ma) and Osborne (1540 Ma) in Australia; Candelaria (~1100 Ma), Salobo (2570–1880 Ma?) and Sossego in South America (Haynes 2000; Hitzman 2000; Porter 2000).

Porter (2000) states that this class of deposit does not represent a single style or a common genetic model, but rather a family of loosely related ores that share a pool of common characteristics. According to Porter (2000):

> …their common link is the association of low Ti iron oxides with the ore. They range from Fe–apatite ores as at Kiruna without any significant Cu–Au, to Fe–REE–F at Bayan Obo, again without any Cu or Au of economic value, to the Fe–Cu–U–Au–REE of Olympic Dam, and the Fe–Cu–Ag without Au at Mantos Blancos, etc. They also occur over an extensive depth range, from the ductile field as at Osborne in Australia to a shallow brittle regime as at Olympic Dam (Pollard, 2000). Many of the Proterozoic deposits are intracratonic, while some of the key Palaeozoic systems are found on the continental margin above a subduction zone (Hitzman, 2000). Indeed there are also deposits, such as Palabora that some say are key members of the family (Vielreicher, Groves & Vielreicher, 2000) but which others believe are unrelated.

Hitzman (2000) notes that the host and surrounding rocks of these deposit types generally show intense alteration, ranging from extensive sodic zones at depth to potassic alteration at intermediate to shallow levels, to sericitic (hydrolytic) alteration and silicification at very shallow levels.

Although some of these iron-rich deposits contain uranium in trace to minor amounts, Olympic Dam is the only known large Proterozoic iron-rich deposit that contains uranium in economic quantities.

Unconformity-related deposits

Unconformity-related deposits occur immediately below and above major unconformities that separate crystalline basement from overlying clastic sandstones of either Proterozoic or, less commonly, Phanerozoic age. The basement metasediments and meta-granites have been altered by lateritic weathering. The overlying sandstones are usually flat lying, but in some cases they have been folded (Dahlkamp, 1993; IAEA, 1996).

Proterozoic unconformity-related deposits

In Proterozoic unconformity-related deposits, the basement rocks are Palaeoproterozoic metasediments mantling Archaean gneissic domes. The overlying sandstones of the Kombolgie Subgroup in the Alligator Rivers region are of late Palaeoproterozoic age. Similarly in the Athabasca and Thelon Basins in Canada, the sedimentation of the overlying sandstones commenced before 1600 Ma (personal communication Dr C. Jefferson, Geological Survey of Canada, August 2000; Kyser and others, 2000). The distributions of the grades and sizes of the deposits are related to their setting with respect to the unconformity and type of host rocks.

Large high-grade uranium or polymetallic deposits occur directly at or slightly above the unconformity (e.g. Cigar Lake, McArthur River (Canada)). Large but medium to high-grade uranium deposits are found below the unconformity (e.g. Rabbit Lake (Canada), Jabiluka 2 (Australia)) and low-grade small deposits may be up to 200 m above the unconformity (e.g. Maurice Bay (Canada)). The style of high-grade unconformity-related deposits at the unconformity, as seen at Cigar Lake, have not been found in the Pine Creek Inlier to date although such deposits could be completely concealed by the cover sandstones. In addition, the cover sandstones have been eroded from above the Ranger, Koongarra and Nabarlek deposits. Thus if any high-grade deposits had been present at the unconformity, they would also have been removed by erosion. Indeed, where the unconformity has been preserved above the Jabiluka deposit, the mineralisation extends more than 500 m below the unconformity, which raises the possibility that a substantial portion of the uranium mineralisation below the unconformity at Ranger, Koongarra, Nabarlek and Rum Jungle may have been removed by erosion.

The high- to very high-grade deposits (1–14% U_3O_8) occur in clay-altered and faulted sandstones immediately above the unconformity. Mineralisation commonly extends into the altered basement rocks and is commonly polymetallic (U+Ni+Co+As). Bitumen often occurs in the mineralised zone. These deposits may have very large reserves: the Cigar Lake and Key Lake deposits, for example, in the Athabasca Basin. The McArthur River deposit (Athabasca Basin) also straddles the unconformity, but does not have extensive clay alteration.

Deposits immediately below the unconformity are usually medium- to high-grade (0.3–1.0% U_3O_8) and dominantly monomineralic. The uranium mineralisation occurs in fault and fracture zones of altered metasediments that often contain graphitic zones: the Rabbit Lake and Eagle Point deposits, for example, in the Athabasca Basin.

Most of the Australian unconformity-related uranium deposits in the Alligator Rivers region, Rum Jungle and South Alligator Valley fields are also related to fault and shear structures and breccia zones. Examples are the Nabarlek, White's and Dyson's deposits. However, the distribution of these deposits is, in addition, controlled by the stratigraphy of the sub-unconformity Palaeoproterozoic rocks, and consequently these are considered to be strata-bound. The Palaeoproterozoic metasediments mantle Archaean gneissic domes. The overlying clastic sediments above the unconformity are late Palaeoproterozoic in age and are usually flat-lying (but in the Rudall region, WA, these sediments are Meso- and Neoproterozoic and have been folded). Strata-bound deposits are within breccia zones or zones of intense close-spaced fracturing related to faults, and the deposits are confined to distinct stratigraphic units within the metasediments. The host rocks are pelitic and carbonate metasediments which have been metamorphosed to amphibolite facies. Retrograde metamorphism (greenschist facies) has been superimposed on these metasediments. Palaeo-weathering of the crystalline basement rocks is usually less than for fracture-bound and clay-bound types of unconformity-related deposits, although in the Alligator Rivers region a truncated regionally extensive palaeo-saprolitic profile is commonly over 50 m thick (Needham, 1988b). Principal uranium minerals are pitchblende and uraninite. Intensive alteration of the host rocks (mainly chlorite alteration, but also sericitisation, argillitisation, and carbonate alteration) surrounds the mineralisation. Some of these deposits (Jabiluka, Koongarra and Ranger 1) contain gold mineralisation. Some smaller deposits are polymetallic, such as those in Rum Jungle that contain copper, lead, cobalt and nickel. Deposits within this group have medium to large resources (some have >200 000 t U_3O_8) and usually have overall low to medium grades (0.2–1% U_3O_8); examples are the Jabiluka, Koongarra, Ranger, Rum Jungle and Kintyre deposits.

Dahlkamp (1993) subdivided the Proterozoic unconformity-related uranium deposits into three subtypes (fracture-related (Rabbit Lake), clay-bound (Cigar Lake) and strata-bound (Jabiluka 2)). We consider that all of these subtypes are part of the same basic deposit model with clay-bound and fracture-bound subtypes as end members of a series. For example, the upper part of the Deilmann orebody of the Key Lake deposit is within a fault structure above the unconformity and is 'clay-bound', whereas the lower part of this orebody is within the same structure in the basement lithologies below the unconformity. The clay-bound deposits, such as Cigar Lake, occupy one end of the series: that is, the Cigar Lake deposit is within a structure and is above the unconformity with very minor extensions of the uranium orebody into the underlying basement. Deposits at the other end of the series, such as Jabiluka, Nabarlek, and Ranger in Australia, and Rabbit Lake and the Gaertner orebody of the Key Lake deposit in Canada, are in structures below the unconformity. The clay-bound type of mineralisation above the unconformity is largely missing from these deposits. In the case of Nabarlek, Ranger and Koongarra, the overlying sandstones have been eroded; at these deposits, mineralisation may or may not have originally been present above the unconformity.

Approximately 20% of Australia's uranium resources are contained in unconformity-related deposits (Table 6). Australia has two main uranium provinces that contain Proterozoic unconformity-related deposits:

- Alligator Rivers uranium field, encompassing Ranger 1, Nabarlek, Jabiluka, Koongarra and Ranger 68 deposits; and

- Rudall Complex, which contains the Kintyre deposit.

A large proportion of Australia's uranium production since 1980 has been from two of these deposits — Ranger (No. 1 and No. 3 Orebodies) and Nabarlek (Table 3). Small deposits have been mined in the Rum Jungle uranium field (Dyson's, White's, Mount Burton and Rum Jungle Creek South) and in the South Alligator Valley uranium field. There are also small deposits in the Turee Creek area (WA).

In the Pine Creek Inlier, the late Palaeoproterozoic sandstone is flat-lying and forms a prominent plateau and escarpment. The uranium deposits are near this escarpment, but it is not suggested here that the unconformity-related deposits are confined to the immediate vicinity of the escarpment. The uranium prospects are known to occur up to 30 km away from the escarpment and the mineralisation at Jabiluka extends to depths of more than 500 m below the unconformity. Unconformity-related deposits may be present and concealed below the Kombolgie Subgroup, and below Mesozoic and Tertiary sediments north of the escarpment.

In the Alligator Rivers, Rum Jungle and South Alligator Valley uranium fields, the deposits and prospects are stratabound in particular stratigraphic sequences, although the three sequences are not stratigraphically equivalent. The deposits are near Archaean basement complexes consisting mainly of gneissic granite. The Rum Jungle, Waterhouse and Nanambu complexes in the Pine Creek Geosyncline are Archaean mantled gneiss domes, and the uranium deposits are in Palaeoproterozoic sedimentary rocks nearby (Ewers & others, 1984).

Field relationships and age dates show that the main period of uranium mineralisation in the Pine Creek Inlier took place after the Barramundi Orogeny (1880–1850 Ma). The mineralisation was probably remobilised several times (Ewers & others, 1984).

The Kintyre deposit is in the Palaeoproterozoic metasediments of the Rudall Complex and occurs in the Rudall River region. The geological setting of the Kintyre deposit is similar to that of the deposits in the Alligator Rivers region.

Phanerozoic unconformity-related deposits

Phanerozoic unconformity-related deposits occur in Proterozoic metasediments below an unconformity at the base of overlying Phanerozoic sandstone. These deposits are small and low-grade: the Bertholene and Aveyron deposits, for example, in France.

The Ranger 68 and Austatom deposits in the Alligator Rivers region are in the Cahill Formation, unconformably overlain by Cretaceous sediments. These deposits are, respectively, within 4 km and 30 km of the escarpment of the Kombolgie Subgroup. The late Palaeoproterozoic Kombolgie/Cahill Formation unconformity was probably close to the current ground surface at Ranger 68 and Austatom. These deposits are probably related to this Palaeoproterozoic unconformity, before retreat of the escarpment due to erosion. It is not known whether any relationship exists between the uranium mineralisation at the two deposits and the later Cretaceous sediment/Cahill Formation unconformity.

Sandstone deposits

Sandstone uranium deposits are contained in fluvial or marginal-marine sandstone. The host rocks are medium- to coarse-grained, poorly sorted, and contain pyrite and organic (plant) matter. The organic matter is either disseminated or forms lignite seams.

Uranium is mobile under oxidising conditions and precipitates under reducing conditions, and thus the presence of a reducing environment is essential for the formation of uranium deposits in sandstone. Hydrogen sulphide, which is an effective reductant and uranium precipitant, can be generated by anaerobic decomposition of organic matter or it can be introduced from underlying or overlying oil or gas horizons, thereby creating a favourable environment in an otherwise unfavourable host rock. Post-Silurian continental sandstone is a potentially favourable host because widespread development of land plants began in the Silurian. This abundant plant growth occurred in humid areas within the region bounded by latitudes 50° North and 50° South of the palaeo-equator. Because of these controls the favourable host rocks are usually confined to post-Silurian sedimentary sequences deposited between palaeo-latitudes 50° North and 50° South (Finch, Wright & Adler, 1982).

Sandstone with a slight dip, such as on the margins of continental basins and coastal plains, is more favourable than sandstone that dips steeply, because the rates of groundwater movement and oxygen intake are slowed enough to preclude destruction of reducing environments. Beds with low dips also provide large surface areas for the capture and introduction of uraniferous groundwater.

Based on shape of orebody and relationship to the depositional or structural environment, sandstone uranium deposits can be subdivided into three types (these may be gradational into each other) (Dahlkamp, 1993): tabular deposits, roll-front deposits and tectonic–lithologic deposits.

- *Tabular deposits* consist of tabular or elongate lenticular zones of uranium mineralisation within selectively reduced sediments. The mineralised zones are oriented parallel to the direction of groundwater flow, but on a small scale the ore zones may cut across sedimentary features of the host sandstone.
- *Roll-front deposits* are crescent-shaped in cross-section, and mineralisation cuts across the bedding and extends from the overlying to the underlying impervious mudstone/siltstone layers. The mineralised zone is convex down the hydraulic gradient. Mineralisation usually has a diffuse boundary with reduced sandstone on the down-gradient side and sharp contacts with the oxidised sands on the up-gradient side.
- *Tectonic–lithologic deposits* occur along permeable fault zones which cut the sandstone mudstone sequence. Mineralisation forms tongue-shaped ore zones along the permeable sandstone layers adjacent to the fault. Often there are a number of mineralised zones 'stacked' vertically on top of each other within sandstone units adjacent to the fault zone.

Sandstone deposits contain a large proportion of the world's known uranium resources, although they are commonly of low to medium grade (0.05 to 0.4% U_3O_8). In each province or basin there are usually many small to medium-size deposits, some of which can contain up to 50 000 t U_3O_8. The cumulative tonnage in the province or basin is often very large — up to several hundred thousand tonnes (Dahlkamp, 1993). Major sandstone uranium provinces include the Powder River Basin in Wyoming, Colorado Plateau and Gulf Coastal Plain of the USA, and the Tim Mersoi Basin of Niger.

Sandstone deposits comprise approximately 7% of Australia's total uranium resources (Table 6). Deposits of this type occur in the Frome Embayment (Beverley, Honeymoon, East Kalkaroo and Goulds Dam), McArthur Basin (deposits in the Westmoreland area), Gunbarrel Basin (Mulga Rock), Carnarvon Basin (Manyingee), Canning Basin (Oobagooma), Amadeus Basin (Angela, Pamela) and Ngalia Basin (Bigrlyi and Walbiri). Large areas of low-grade uranium mineralisation are known in Eocene palaeochannel sediments of the Eucla Basin in the Eyre Peninsula region (SA). These include the Warrior deposit near Tarcoola, and the Yarranna deposit east of Ceduna.

In the southern portion of the Frome Embayment, uranium deposits occur in Tertiary palaeochannel sands. Oxidising groundwater, moving slowly through the channels, leached uranium from the sand and reprecipitated it at the redox interface, to form roll-front and tabular deposits.

The Redtree, Junnagunna and Huarabagoo deposits in the Westmoreland area are in late Palaeoproterozoic sandstone of the Westmoreland Conglomerate along the south-eastern margin of the

McArthur Basin. This sandstone is much older than the host rocks of typical sandstone uranium deposits, and fossilised plant matter is absent. Oxidising formation-waters within the host sandstone transported uranium during circulation associated with heat flows. Mineralisation was precipitated within the sandstone adjacent to basic dykes and an overlying basalt flow. The abundant supply of divalent iron in these basic rocks created a reducing environment. The basalt flow also acted as a physico–chemical barrier restricting the circulation of formation-waters (Schindlmayr & Beerbaum, 1986).

Along the northern margins of the Amadeus and Ngalia Basins, uranium deposits occur in Late Devonian to Carboniferous continental sandstone. The geological setting is similar in both basins. The sandstones contain abundant plant remains, and the uranium was deposited at redox boundaries.

The Mulga Rock deposit is in Eocene palaeochannel sediments along the south-western margin of the Gunbarrel Basin. These palaeochannel sediments overlie metamorphic basement of the Yilgarn Craton and the Albany–Fraser Orogen.

In the Carnarvon Basin, the host rock of the Manyingee deposit is Cretaceous sandstone filling a palaeochannel eroded in the basement. Uranium has accumulated at a redox boundary in the sandstone.

In the Canning Basin, the Oobagooma deposit is hosted by Early Carboniferous sandstone in the Yampi Embayment.

Surficial deposits

Surficial uranium deposits are broadly defined as young (Tertiary to Recent) near-surface uranium concentrations in sediments or soils. These deposits usually have secondary cementing minerals including calcite, gypsum, dolomite, ferric oxide and halite. Uranium deposits in calcrete (calcium and magnesium carbonates) are the largest of the surficial deposits. The calcrete bodies are interbedded with Tertiary sand and clay, which are usually cemented by calcium and magnesium carbonates. Calcrete deposits form in regions where uranium-rich granites were deeply weathered in a semi-arid to arid climate. Surficial uranium deposits also occur in peat bogs, karst caverns and soils.

In Western Australia, the calcrete uranium deposits occur in valley-fill sediments along Tertiary drainage channels (e.g. Yeelirrie) and in playa lake sediments (e.g. Lake Maitland). These deposits overlie Archaean granite and greenstone basement of the northern portion of the Yilgarn Craton. The uranium mineralisation is carnotite (hydrated potassium uranium vanadium oxide).

The Yeelirrie deposit is by far the world's largest surficial deposit. It contains 52 500 t U_3O_8 in resources averaging 0.15% U_3O_8. Other significant deposits in Western Australia include Lake Way, Centipede, Thatcher Soak and Lake Maitland. Calcrete deposits represent approximately 5% of Australia's total reserves and resources of uranium.

Calcrete uranium deposits also occur in the Central Namib Desert of Namibia, the largest being the Langer Heinrich which has 8970 t U_3O_8 in resources averaging 0.109% U_3O_8 at a 0.05% cut-off. At a lower cut-off of 0.02% U_3O_8, the deposit has 34 300 t U_3O_8 at an average grade of 0.056% U_3O_8 (Acclaim, 1999). Other small deposits are Trekkopje, Tubas and Aussinanis.

Metasomatite deposits

Metasomatite deposits consist of unevenly disseminated uranium in structurally deformed rocks that were affected by sodium metasomatism. Metasomatic host rocks include albitites, aegirinites and alkali amphibole rocks. Principal ore minerals are U–Th oxides and silicates, including thorium–rich uraninite, uranothorite and thorite, and U–Ti oxide minerals including brannerite. Most of these minerals are refractory and are difficult to beneficiate using conventional acid-leach processes.

The host rocks show several types of alteration. Typically the rocks show sodium-metasomatism which results in enrichment in Na_2O and depletion of SiO_2. Hematite and carbonate alteration is usually present. Albitites that host the mineralisation often occur along mylonitic zones or major fault zones.

Two subtypes are defined on the basis of host rock:

- *metasomatised granite*; uranium deposits occur in albitites and sodium-rich granite host rocks, such as the Ross Adams deposit, Alaska;
- *metasomatised metasediment*; uranium deposits occur in metasediments with metasomatic albite–aegerine, albite–arfvedsonite–aegerine and other sodium silicates, such as the Zheltye Vody deposit in the Krivoy Rog area, Ukraine, and Valhalla deposit, Australia.

Metasomatite deposits are small and generally contain less than 1000 t U_3O_8. Ore grades are low, usually less than 0.2% U_3O_8, but may range up to 3% U_3O_8. The largest deposits of this type are the Ross Adams, Zheltye Vody and Valhalla deposits.

Less than 2% of Australia's uranium resources are in this type of deposit. Metasomatite deposits occur in the Eastern Creek Volcanics north of Mount Isa, the largest of them being Valhalla, Skal and Anderson's Lode. The Valhalla deposit is hosted by breccciated metasediments (carbonaceous shale and mafic tuff), altered basalt and albitite. The host rocks show intense sodic and hematitic alteration, and the uranium–vanadium mineralisation is closely associated with the alteration. Skal and Anderson's lode are similar to Valhalla but smaller. There are more than 100 other small uranium deposits and prospects of this type in the Eastern Creek Volcanics.

Metamorphic deposits

Metamorphic-type uranium deposits occur in metasediments and/or metavolcanics, generally without direct evidence of post-metamorphic mineralisation. Examples include the deposits at Forstau, Austria (OECD/NEA & IAEA, 2000). Principal uranium minerals are pitchblende and/or uraninite. Metamorphic deposits result from regional metamorphism of uraniferous sediments or volcanics containing uranium mineralisation.

Metamorphic deposits are most commonly low-grade (0.001–0.15% U_3O_8) and contain small resources of subeconomic magnitude (up to 1000 t U_3O_8) (Dahlkamp, 1993).

In the Mary Kathleen zone, east of Mount Isa, uranium mineralisation is hosted by skarns within metamorphosed calcareous rocks of the Corella Formation. The largest is the Mary Kathleen deposit, which was mined during two periods: 1958–63 and 1976–82. The Mary Kathleen deposit is considered to be a skarn-hosted metamorphic–hydrothermal deposit. Uranium–rare earth mineralisation is hosted by skarn that formed during a period of regional metamorphism and deformation. Mineralisation and host skarn body are closely associated with a major shear zone that was active during deformation and regional metamorphism. Several other small uranium prospects also occur in the Mary Kathleen zone.

Volcanic deposits

Volcanic deposits are associated with felsic to intermediate volcanic rocks and their sedimentary derivatives. These deposits are typically associated with volcanic cauldron subsidence structures and co-magmatic granitic intrusions, ring dykes, ignimbrites, pyroclastics and intracaldera volcaniclastics. Uranium occurs in structure-bound or strata-bound deposits. Structure-bound mineralisation is found in veins associated with shear zones, fracture zones, faults, volcanic intrusions, dykes and diatremes. Strata-bound mineralisation consists of disseminations and impregnations in permeable flows, flow breccias and clastic sediments.

The principal uranium mineral in volcanic deposits is pitchblende, which is usually associated with molybdenite and minor amounts of Pb, Sn and W mineralisation. Associated gangue minerals are typically fluorite, quartz and carbonates.

Type examples of volcanic deposits are the Michelin deposit, Canada; Nopal 1 deposit, Mexico; Macusani deposit, Peru; and numerous deposits in China and Kazakhstan.

Volcanic deposits range in size and can contain up to several thousand tonnes U_3O_8. Grades range from 0.02% to 0.2% U_3O_8. Typically there are a number of small deposits in a district or cauldron subsidence area. Districts usually have several thousand tonnes U_3O_8.

In Australia, volcanic deposits are quantitatively very minor. In the Georgetown–Townsville uranium field, several volcanic-type deposits containing uranium–fluorine–molybdenum mineralisation are related to Late Carboniferous–Early Permian acid volcanics. Maureen and Ben Lomond are the largest of these deposits. The volcanic complexes and comagmatic intrusions are preserved in fault-bounded cauldron subsidence areas. Mineralisation is hydrothermal and the deposits have accumulated in shallow zones of high porosity and permeability. Intensely jointed rocks, breccia pipes, fault zones, unconformities and permeable sedimentary rocks are hosts for mineralisation.

Intrusive deposits

Intrusive deposits are associated with intrusive or anatectic rocks. Among the several types of granitic rock that form hosts for this type of deposit are:

- alaskite, e.g. Rossing deposit, Namibia;
- quartz-monzonite, e.g. Bingham Canyon porphyry copper deposit, USA;
- carbonatite, e.g. Phalaborwa deposit, South Africa;
- peralkaline syenite, e.g. Kvanefjeld deposit, Greenland;
- pegmatite, e.g. Madawaska deposit, Canada.

At the Rossing deposit, syntectonic medium to coarse-grained alaskite has been emplaced as bodies ranging from large stocks and domes to tabular dykes, within isoclinally folded, highly metamorphosed and migmatised metasediments.

Deposits in this category make up a large proportion of the world's uranium resources. Intrusive deposits are low to very low grade (up to 0.05% U_3O_8) but may contain substantial resources. Initial reserves at the Rossing deposit were approximately 130 000 t U_3O_8 with average grade of 0.03 to 0.04% U_3O_8.

Only a minor proportion of Australian uranium resources are in intrusive-type deposits and the grades for most of these are low. In the Olary Province (SA), deposits at Radium Hill, Crocker Well and Mount Victoria are associated with Mesoproterozoic intrusives (approximately 1580 Ma; Fig. 5), mainly granite, alaskite, pegmatite and migmatites.

At Radium Hill, uranium–rare earth orebodies occurred in narrow, steeply dipping pegmatitic veins in sericitic shear zones within Palaeoproterozoic quartzo-feldspathic gneiss and amphibolite. The deposits were mined for radium from 1906 to 1931, and for uranium from 1954 to 1961. At Crocker Well, thorian brannerite occurs in fractures and breccia zones in sodic granite, trondhjemite and sodic alaskite. At Mount Victoria, the mineralisation occupies a system of fractures in migmatitic granite and gneiss.

In the Gascoyne Block (WA), alaskite and pegmatite which intrude the Morrissey Metamorphic Suite (Palaeoproterozoic) contain zones of low-grade uraninite mineralisation (Mortimer Hills area). This mineralisation is similar to the Rossing deposit.

In the Mordor Igneous Complex, 65 km north-east of Alice Springs, small zones of uranium silicate mineralisation occur in syenitic intrusives.

Vein deposits

Vein deposits of uranium are those in which uranium minerals fill cavities such as cracks, veins, fissures, pore spaces, breccias and stockworks. The dimensions of the openings have a wide range, from the massive veins of pitchblende at Jachymov deposit (Czech Republic), Schinkolobwe deposit (Democratic Republic of the Congo) and Port Radium deposit (Canada) to the narrow pitchblende-filled cracks, faults and fissures in some of the ore bodies in Europe, Canada and Australia. Two subtypes are recognised:

- *veins related to granites*; for example Fanay deposit (France) and Jachymov deposit (Czech Republic);
- *veins unrelated to granites*; for example Schwartzwalder deposit, Colorado, in metamorphic rocks, and Schinkolobwe deposit in dolomite and carbonaceous shale.

Vein deposits generally range in grade from 0.1% to 2.4% U_3O_8. They can contain up to 24 000 t U_3O_8, but make up only a small proportion of the world's uranium resources.

In Australia, vein deposits are quantitatively very minor. Many small vein deposits occur in various geological settings, including Proterozoic metamorphics near Port Lincoln, in the Mount Lofty Ranges, and in the Peake and Denison Ranges (all in SA), and Palaeozoic granites in the Lachlan and New England Fold Belts (NSW, Victoria and Tasmania).

Quartz-pebble conglomerate deposits

Detrital uranium occurs in some Archaean–early Palaeoproterozoic quartz-pebble conglomerates that unconformably overlie granitic and metamorphic basement. Quartz-pebble conglomerate uranium deposits occur in conglomerates deposited in the range 3070–2200 Ma (Skinner, 1975; Roscoe, 1995; Misra, 2000). Fluvial transport of detrital uraninite was possible at the time because of the prevailing anoxic atmosphere (Myers, 1975; Robertson, 1975; Roscoe, 1975). Some authors have suggested that deposition of such uraniferous conglomerates does not require a totally anoxic atmosphere, i.e. that they could have been deposited in an atmosphere containing a small amount of oxygen (Grandstaff, 1975). The uraniferous conglomerates occur in Archaean–Palaeoproterozoic basin sequences and usually crop out around the edges of the basins. The conglomerates are highly pyritic and the pebbles are cemented by chlorite and sericite. The uranium occurs in the matrix principally as uraninite in association with other heavy minerals, some containing thorium and/or uranium. Carbon occurs in these deposits as coatings and thin seams, probably originally primitive plant material. A considerable proportion of the uranium was partly dissolved and reprecipitated during diagenesis. The presence of carbon in localised areas may have played a role in this post-depositional redistribution (Skinner, 1975). The uraniferous conglomerates are light to dark grey, with virtually no evidence of oxidation.

The quartz-pebble conglomerate deposits make up a major proportion of the world's uranium resources. They are among the lowest-grade uranium deposits mined. Where uranium is recovered as a by-product of gold mining, the grade may be as low as 0.01% U_3O_8. In those deposits that were mined exclusively for uranium (e.g. Elliott Lake, Ontario), average grades ranged as high as 0.15% U_3O_8. Individual deposits contain from 6000 t to 180 000 t U_3O_8. Major examples are the Elliot Lake deposits in Ontario and the Witwatersrand gold–uranium deposits in South Africa.

With the decline in uranium market prices after the early 1980s, the mining operations in the Elliott Lake district became uneconomic and these mines were closed. The last mining operation (Stanleigh mine) ceased production in 1996. Consequently, the only conglomerate deposits now being mined worldwide are the Witwatersrand deposits where uranium is a by-product of gold mining.

Quartz-pebble conglomerates containing uranium (and gold) are known to occur in four provinces in Western Australia: Hamersley Basin, Yerrida Basin, Halls Creek Orogen and the Pilbara Craton. A considerable amount of exploration and drilling for palaeoplacer deposits of uranium and gold in these conglomerates has been carried out, particularly in the Hamersley Basin. However, to date, no uranium or gold concentrations of commercial significance have been identified.

In the Hamersley Basin, several zones of low-grade uranium–gold mineralisation occur in Archaean quartz-pebble conglomerate beds of the lower Fortescue Group (mainly the Hardey Sandstone; about 2700 Ma) and within the Gorge Creek Group (about 3000 Ma) (Carter & Gee, 1988). In the Halls Creek area, low-grade uranium–gold mineralisation occurs 35 km north-east of Halls Creek, in quartz-pebble conglomerate of the Archaean–Palaeoproterozoic Saunders Creek Formation. Low-grade mineralisation has also been intersected during exploration in quartz-pebble conglomerates in the Yerrida Basin and Pilbara Craton (Lalla Rookh Sandstone).

Collapse breccia pipe deposits

Collapse breccia pipe deposits occur in circular, vertical collapse structures filled with down-dropped coarse fragments and fine matrix of the penetrated sediments. The collapse pipes are 30–200 m in diameter and up to 1000 m deep (Dahlkamp, 1993). Uranium mineralisation is mostly within permeable sandstone breccias within the pipe. The principal uranium mineral is pitchblende. The best known examples of this type are deposits in the Arizona Strip in Arizona, USA. Several of these have been mined in recent years.

Resources within individual breccia pipes range up to 2500 t U_3O_8 and average grades are between 0.3 and 1% U_3O_8. Known reserves of the Arizona Strip area are about 15 000 t U_3O_8. There are no known examples of this type of deposit in Australia.

Phosphorite deposits

Sedimentary phosphorites contain low concentrations of uranium in fine-grained apatite. Uranium concentrations are 0.01–0.015% U_3O_8. Very large phosphorite deposits occur in the USA (Florida and Idaho), Morocco and Middle Eastern countries and these are mined for phosphate. Where phosphoric acid is produced, uranium is, in some instances, extracted as a by-product; for example, in Florida.

The Cambrian phosphorites at the Duchess deposit in north-west Queensland are being mined for phosphate. Average uranium content of the phosphate ores is 0.0126% U_3O_8 (126 ppm), but this is not extracted from the ores.

Lignite

Uranium mineralisation occurs in lignite and in clay and sandstone immediately adjacent to the lignite, in the Serres Basin, Greece, for example, and in North and South Dakota, USA. Uranium has been adsorbed onto carbonaceous matter and consequently no discrete uranium minerals have formed. Uranium grades are very low and average less than 0.005% U_3O_8. The uranium content of this type of mineralisation is too low to warrant commercial extraction (Dahlkamp, 1993). There are no known significant uranium deposits of this type in Australia.

Black shale deposits

Black shale-related uranium mineralisation consists of marine organic-rich shale or coal-rich pyritic shale, containing synsedimentary disseminated uranium adsorbed onto organic material. Examples include the uraniferous alum shale in Sweden, the Chatanooga shale in the USA, deposits in the Guangxi Autonomous Region, China, and the Gera–Ronneburg deposit, Germany (OECD/NEA & IAEA, 2000). The Chatanooga Shale extends over an area of 80 000 km^2, is approximately 10 m thick and has an average grade of 0.0057% U_3O_8. Although this shale contains very large quantities of uranium these resources are uneconomic. There are no commercial uranium deposits of this type, and there are no known significant uranium deposits of this type in Australia.

Other types of deposits

There are also uranium deposits, of other types, in the Jurassic Todilto Limestone in the Grants district, New Mexico, USA.

Time-bound distribution of types of uranium deposits

The ages of uranium deposits worldwide show that various types of deposits formed in particular periods of geological time. The age distribution of deposits precipitated from groundwaters or surface waters can be broadly correlated with the evolution of atmospheric oxygen through geological time.

Uranium deposits hosted by quartz-pebble conglomerates are restricted to conglomerates deposited between 3070 Ma and 2200 Ma (Skinner, 1975; Roscoe, 1995; Misra, 2000) (Fig. 5). As stated already, fluvial transport of detrital uraninite was possible during this time because of the prevailing anoxic atmosphere in the Archaean and early Palaeoproterozoic (Robertson, 1975; Roscoe, 1975).

The transition from an anoxic (reducing) to an oxidising atmosphere occurred around 2400–2000 Ma (Misra, 2000), and is marked by the disappearance of significant deposits of detrital uraninite in conglomerates. During this period, redbed sandstones first appeared in sedimentary sequences worldwide (Solomon & Sun, 1997). The Earth's atmosphere was sufficiently oxidising after 2200 Ma to allow uranium to dissolve in oxidising surface waters and groundwaters, and be transported in solution. This has continued through geological time to the present.

The largest unconformity-related deposits were formed in the Proterozoic. Ranger, Jabiluka and Koongarra were deposited between 1760 Ma and 1400 Ma. Age-dating of the sequence associated with the Kintyre deposit suggests that the mineralisation is younger than 1070 Ma (Bagas, Camacho & Nelson, in press). During the Proterozoic, the atmosphere was gradually evolving and the oxygen-content was increasing. Groundwaters within Proterozoic continental sandstone sequences were sufficiently oxidising for uranium to be transported as the uranyl ion during diagenesis. However, reducing conditions existed in the groundwaters within the metasediments below the unconformity, due to the presence of carbon and divalent iron in these rocks. Uranium was deposited at the redox interface between these two types of fluids. This interface occurred either where oxidising fluids migrated downwards into breccia zones and faults in the metasediments, or where reduced fluids migrated upwards along structural zones and mixed with oxidised fluids moving laterally within the overlying sandstones.

Unconformity-related deposits also formed in the Phanerozoic; however, these younger deposits are much smaller than those formed in the Proterozoic.

During the formation of sandstone-type deposits, uranium was transported by oxidising surface waters and groundwaters moving through continental sandstone sequences. Uranium was precipitated where

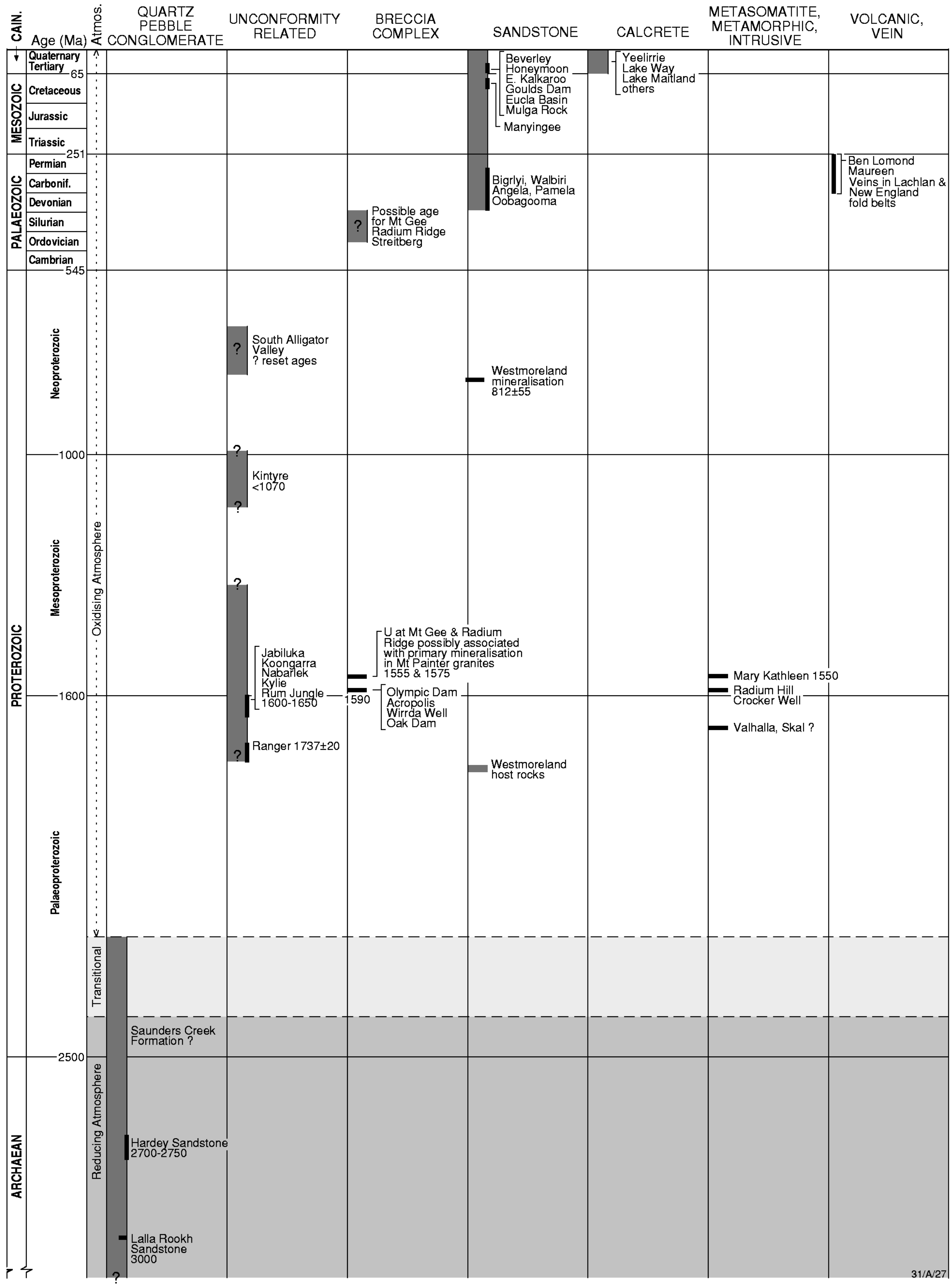

Figure 5. Ages of Australian uranium deposits, and age-ranges (vertical bars) of the major types of deposits worldwide. For sandstone-type deposits the ages shown are those of the host rocks; for the other deposits the ages include the oldest mineralisation, which is known at some deposits to have been subsequently remobilised.

these oxidising solutions interacted with localised reducing conditions in the sandstones. Reducing conditions within these continental sandstones were caused by:

- anaerobic decomposition of plant material; or
- abundant supply of divalent iron associated with interbedded basic volcanics and intrusive dykes.

Organic matter is either disseminated within these continental sandstones or occurs as lignite seams. Widespread development of land plants began in the Silurian, particularly in humid climatic zones. Post-Silurian continental sandstones host the majority of sandstone uranium deposits.

Some uranium deposits are hosted by sandstones which are older than Silurian. In these, the uranium was transported by oxidising groundwaters and precipitation occurred adjacent to interbedded basic volcanics or intrusive basic dykes. The age of these uranium deposits is usually much younger than the age of the host sandstones.

In Australia, most of the sandstone uranium deposits are in sedimentary rocks that range in age from Late Devonian to Tertiary. The exceptions are the Westmoreland deposits, which occur in Palaeoproterozoic strata; it has been proposed (Schindlmayr & Beerbaum, 1986) that the reducing conditions resulted from the abundant supply of divalent iron in the vicinity of basaltic flows and basic dykes.

Calcrete-hosted uranium deposits occur in Tertiary palaeochannel sediments. Uranium was transported in solution by groundwater and deposited in the calcrete layers in an oxidising environment.

The Olympic Dam breccia complex deposit formed at approximately 1590 Ma. The age of this deposit is the same as the general age of several large Proterozoic iron-rich deposits whose origins are related to alkali-rich volcanics and intrusives. These include Kiruna iron ore deposits (Sweden) and iron ore deposits in southeast Missouri (USA).

At Olympic Dam, much of the hydrothermal brecciation occurred in a near-surface environment where phreatic activity formed a large eruption crater. Precipitation of metals was probably due to redox reactions resulting when the ascending, hot, reduced, Fe-rich waters mixed with cooler meteoric and/or lacustrinal waters occupying the near surface parts of the breccia complex (Cross, Daly & Flint, 1993; Haynes & others, 1995). The meteoric and lacustrine waters were oxidising, and were derived from a provenance containing mafic volcanic rocks. The groundwater was probably responsible for transport of Cu, U, Au and most of the S into the breccia complex, where it reacted with the hotter water that introduced most of the Fe from below.

Uranium–rare earth elements deposits within hematite breccias in the Mount Painter area are considered to be Palaeozoic in age; however, recent studies indicate that the primary mineralisation may have been Mesoproterozoic which is the age of the host granites.

The types of uranium deposits that formed directly from magmatic sources (such as metasomatite, volcanic, intrusive, and vein-type deposits) are not restricted to particular periods of geological time. Their formation is not dependent upon interaction with oxidising surface waters or oxidising groundwaters.

BRECCIA COMPLEX DEPOSITS

Australia has breccia complex deposits of uranium in South Australia. The Stuart Shelf area of the Gawler Craton contains the world's largest uranium deposit at Olympic Dam. Other breccia complex deposits occur in the Mount Painter field, 250 km east-north-east of Olympic Dam.

STUART SHELF AREA OF GAWLER CRATON

The discovery of the Olympic Dam deposit has been described by Haynes (1979), O'Driscoll (1985), Reeve and others (1990), Lalor (1991), Woodall (1992) and Smith (1993). The deposit was discovered in 1975 by Western Mining Corporation Ltd (WMC). The discovery resulted from the development and application of a conceptual model for the formation of sediment-hosted copper deposits. This model postulated that oxidation and brecciation of basalts would release copper, which would be transported by groundwaters and deposited in reducing sedimentary environments.

The Stuart Shelf province was chosen as a prospective area because it was considered to be underlain by altered basalts and to contain favourable host rock environments for sedimentary copper deposits (Lalor, 1991). Photomosaic lineaments were plotted for the Stuart Shelf province as part of a tectonic study of the area.

The Olympic Dam area was selected for drill testing because it has: (i) coincident gravity and magnetic anomalies (indicating the possibility of basalt at depth), and (ii) favourable tectonic lineaments, indicating the presence of major tectonic structures along which the mineralised fluids would transport copper to the overlying sediments.

Drill hole RD1, drilled in 1975 intersected 38 m averaging 1.0% Cu between 353 m and 391 m depth. Further holes were drilled in the immediate vicinity, some of which also intersected mineralisation of similar grades. Drill hole RD10, drilled in 1976, intersected 170 m assaying 2.1% Cu and 0.06% U_3O_8.

In 1979, a joint venture was formed between WMC and BP Minerals to further outline and evaluate the deposit. A mining and metallurgical feasibility study was completed by mid-1985, and the decision to establish an underground mining operation was made in December 1985. Production commenced in 1988. Initially, approximately 2.2 Mt ore was treated annually to produce 65 000 t refined copper and 1400 t U_3O_8. Significant amounts of refined gold and silver were also produced.

In 1993, WMC Limited acquired full ownership of Olympic Dam. The mine and processing facilities are now operated by WMC (Olympic Dam Corporation) Pty Ltd, a wholly owned subsidiary of WMC Ltd.

Mining and milling operations and project expansions at Olympic Dam have been described earlier, in the chapter called 'Development and Production'.

Geological setting

The following description of the regional geological setting of the Olympic Dam deposit summarises Oreskes and Einaudi (1990); Reeve and others (1990); Johnson and Cross (1991); Creaser and Cooper (1993); Cross and others (1993); Drexel, Preiss and Parker (1993); Smith (1993); Western Mining Corporation (WMC) (1993); Daly, Fanning and Fairclough (1998) and Reynolds (2000).

The Olympic Dam deposit occurs within granitic rocks of the north-eastern portion of the Gawler Craton, where a sequence of undeformed Neoproterozoic and Cambrian marine platform sedimentary rocks

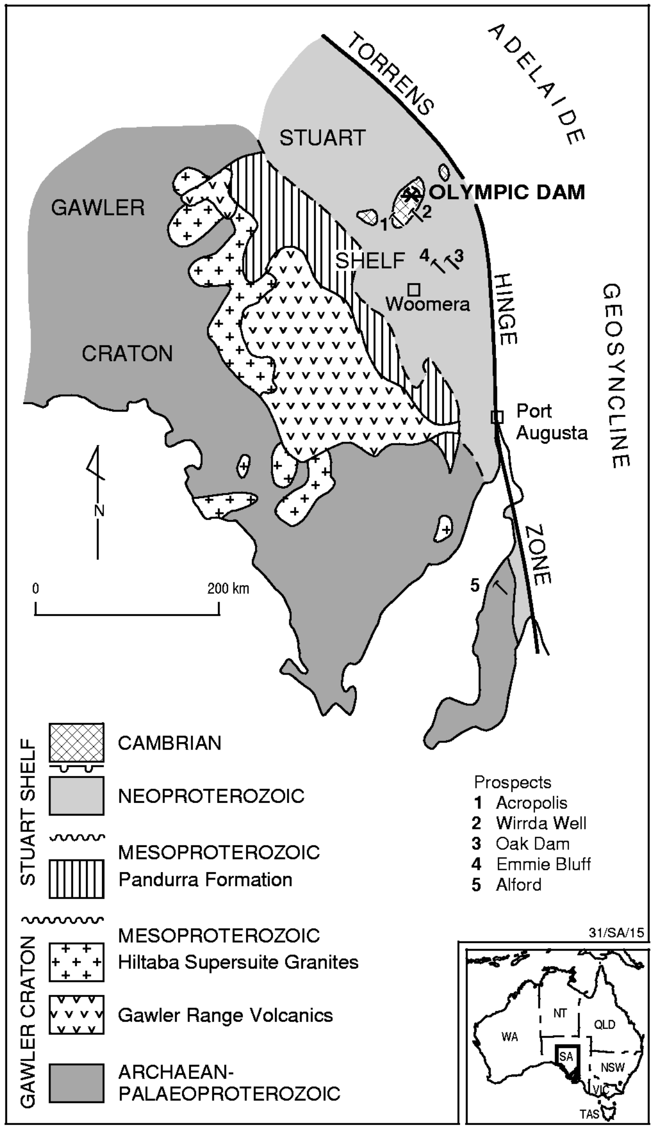

Figure 6. Location plan and simplified regional geology of the Gawler Craton and Stuart Shelf, South Australia (after Reeve & others, 1990)

unconformably overlies the Gawler Craton (Fig. 6). This region is part of the Stuart Shelf geological province.

The Torrens Hinge Zone marks the boundary between the Stuart Shelf and the Adelaide Geosyncline. It also defines the eastern and north-eastern margins of the Gawler Craton.

Below the Neoproterozoic and Cambrian sediments, the Gawler Craton consists of deformed Palaeoproterozoic metasediments and granitic rocks (Hutchison Group and Lincoln Complex), which are overlain by flat-lying felsic and mafic volcanics and siltstones. These volcanics are erosional remnants of the Mesoproterozoic Gawler Range Volcanics (Parker, 1990).

The Palaeoproterozoic rocks are intruded by granitic plutons of the Hiltaba Suite (Mesoproterozoic). In the Olympic Dam area, an undeformed batholithic complex (the Burgoyne batholith) is a part of the Hiltaba suite that intrudes the deformed metasediments and granitic rocks (Reeve & others, 1990). The Burgoyne batholith extends over an area of approximately 2400 km^2 below the Stuart Shelf. Plutonic rocks within the batholith range in composition from syeno-granite to quartz monzodiorite. The Roxby Downs Granite, a pink to red-coloured syeno-granite, is a member of this batholith.

Evidence from geophysical data and from dykes and other small intrusive bodies within the Olympic Dam orebody suggests that an ultramafic–mafic pluton occurs at depth within the batholith.

The orebody occurs within the hematite-rich Olympic Dam Breccia Complex (ODBC), which is a large hydrothermal breccia complex entirely within the Roxby Downs Granite. The ODBC and adjacent areas of Roxby Downs Granite form a basement high. The peak of this high is above the central portions of the ODBC where the basement high is approximately 260 m below surface. Depth to basement increases to 500 m at distances of several kilometres away from the centre of the ODBC.

The breccia body is broadly funnel-shaped and elongated in a north-westerly direction. The central core of barren hematite–quartz breccia is intruded by diatremes and dykes and surrounded by mineralised hematite-rich breccias. The outer zone consists of variably brecciated, variably altered Roxby Downs Granite. The central core and mineralised breccias are ~3 km by 3.5 km in plan with a north-westerly arm 3 km long and 300–500 m wide. Individual breccia bodies in the northern and north-western parts of the breccia complex also trend north-west and dip steeply, reflecting larger scale contemporaneous strike-slip faulting (Sudgen & Cross 1991 in Daly & others, 1998).

The intrusive ages for the Roxby Downs Granite and other plutons of the Burgoyne batholith were determined from U–Pb zircon ages to be in the range from 1598 ± 2 to 1588 ± 4 Ma (Mortimer & others, 1988; Creaser & Cooper, 1993). The age of the Roxby Downs Granite is 1588 ± 4 Ma (Creaser & Cooper, 1993). The U–Pb ages of zircons from fragmental dykes and tuffs intruding the Olympic Dam deposit are almost the same as the age of the Roxby Downs Granite (Cross & others, 1993; Johnson & Cross, 1995).

Ages determined by Mortimer and others (1988), Johnson and Cross (1991) and Creaser and Cooper (1993) for the Gawler Range Volcanics are the same as those of the Burgoyne batholith. Thus the Burgoyne batholith is coeval with the Gawler Range Volcanics and the Hiltaba Suite granitoids.

The undeformed Neoproterozoic and Cambrian marine sedimentary rocks which overlie the Gawler Craton consist mainly of shale, sandstone, quartzite, dolomite and limestone (Cambrian Andamooka Limestone). For detailed descriptions of the Stuart Shelf sedimentary sequence refer to Parker (1990); and Drexel and others (1993).

Olympic Dam deposit

The Olympic Dam deposit is hosted by the ODBC, which comprises a variety of breccia types (Figs 7 and 8). There is a complete gradation from granite breccias through hematite–granite breccias to hematite-rich breccias.

Granite-rich breccias vary from fractured granite, through granite breccias with altered granite-derived matrix, to highly altered, matrix-rich breccias with relict granite fragments. The matrix of these granite-rich breccias consists of fine granitic material together with sericite, chlorite, hematite and variable amounts of barite, fluorite, sulphides and uranium minerals.

The *hematite-rich breccias* have been subdivided into three general groups (Reeve & others, 1990):

- hematite–quartz breccias,
- hematite breccias, and
- heterolithic hematitic breccias.

Hematite–quartz breccias comprise fragments of hematite and quartz in a matrix of microgranular hematite and quartz. This breccia type is essentially devoid of copper and uranium mineralisation. Locally this type of breccia contains abundant barite veins and vein fragments.

Hematite breccias contain clasts and matrix composed mainly of hematite. Hematite breccias are the least abundant of the three main types of hematite-rich breccias, but they host a significant proportion of the ore mineralisation. These breccias are typically steely grey to black in colour. Minor components include quartz, fluorite, barite and altered granite-derived mineral fragments.

Heterolithic hematitic breccias include intermediate members of the range from granitic to hematite breccias. This category is the most abundant of the hematite-rich breccias and it hosts most of the copper–uranium–gold–silver ore. Hematite clasts range from dark red–brown through steel grey to jet-black in colour. Other clasts include altered granite fragments, highly altered ultramafic, mafic and felsic intrusives, finely laminated hematitic siltstone and sandstone, and massive to poorly layered arkose-like rocks. These breccias also include variable proportions of sericite, chlorite, quartz, barite, siderite and fluorite.

Within the ODBC there is a broad zonal distribution of the major rock types. The central core of the complex is barren hematite–quartz breccias, with several localised diatreme structures (Figs 7 and 8). The hematite–quartz core is flanked to the east and west by zones of intermingled hematite-rich breccias and altered granitic breccias. These zones are approximately 1 km wide and extend almost 5 km in a north-west–south-east direction. Virtually all the economic copper–uranium mineralisation is hosted by hematite-rich breccias (heterolithic hematitic breccias and hematite breccias) here. Heterolithic hematitic breccias form a large number of discrete irregular, elongate or lenticular bodies within this broad zone. Hematite breccias form relatively small irregular bodies either within or on the margins of larger heterolithic hematitic breccia bodies.

This broad zone is surrounded by granitic breccias extending up to 3 km beyond the outer limits of the hematite-rich breccias. The outer limits of the ODBC are gradational with the Roxby Downs Granite.

Dykes and intrusive tuffs of ultramafic, mafic and felsic rock types intrude into the ODBC, particularly the eastern and southern parts of the complex. These intrusive rocks are closely associated with volcanic diatreme structures (Reeve & others, 1990; WMC, 1993). The diatremes contain ‘subsided subaerial tuffs and conglomerates which pass laterally and downwards into phreatomagmatic breccias’ (WMC, 1993).

Localised zones of volcaniclastics broaden upwards, and near the unconformity they include: surficial volcaniclastic rocks, mainly laminated ash and conglomerate (containing fragments of Gawler Range Volcanics), and reworked hydrothermal breccias (Fig. 8). These volcaniclastic rocks appear to have accumulated in maar craters produced by phreatomagmatic eruptions (Reeve & others, 1990; Cross & others, 1993).

The Olympic Dam deposit contains iron, copper, uranium, gold, silver and rare earth elements (mainly cerium and lanthanum). Only copper, uranium, gold and silver are recovered. Ore grade copper–uranium–gold–silver mineralisation forms a large number of ore zones mostly within heterolithic breccias and hematite breccias. The central core and mineralised breccias are approximately 3 km by 3.5 km (in plan) with a north-westerly arm 3 km long and 300–500 m wide.

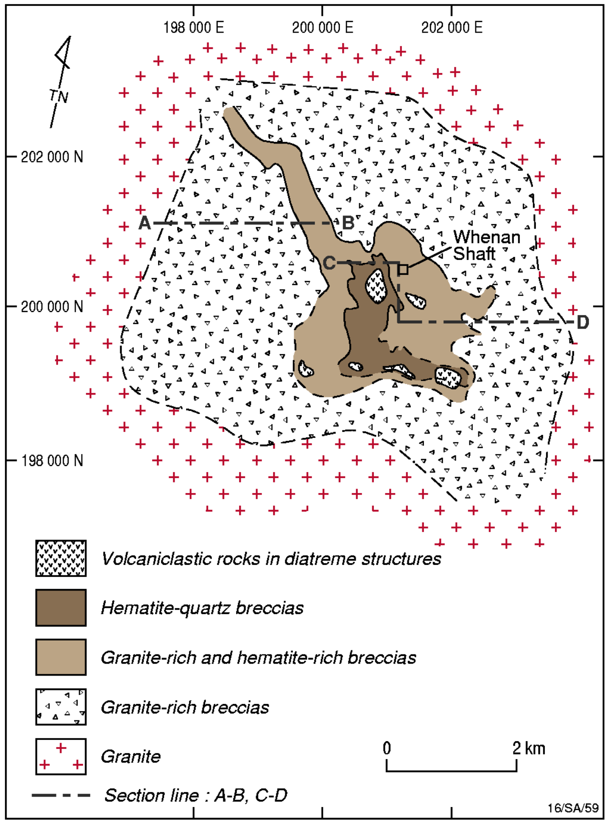

Figure 7. Simplified geological plan of the Olympic Dam Breccia Complex (modified after Reeve & others, 1990)

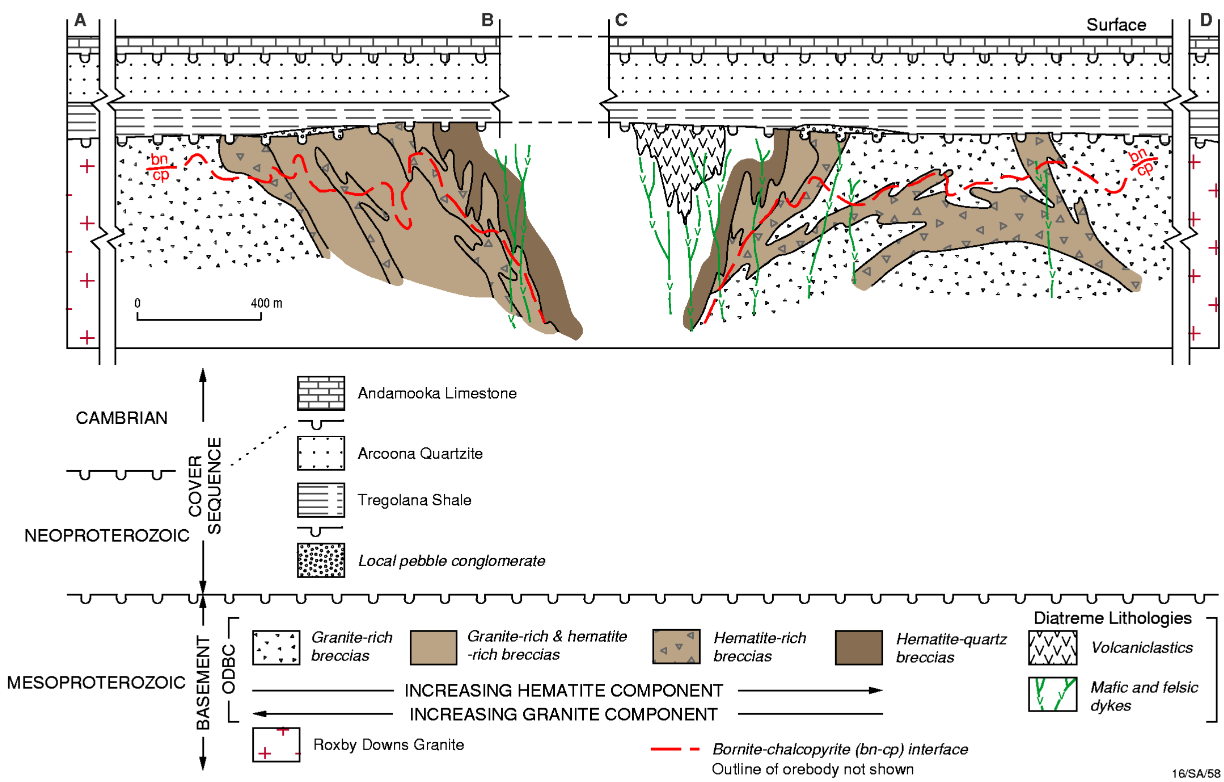

Figure 8. Simplified geological cross-section of the Olympic Dam Breccia Complex (modified after Reeve & others, 1990). Refer to Figure 7 for location of section A–B.

The principal copper sulphide minerals are chalcopyrite, bornite and chalcocite. Throughout the deposit there is a well-developed zonal distribution of the principal copper sulphide minerals (Fig. 8). Chalcopyrite (and pyrite) occur in the deeper and outer parts of the orebody whereas bornite and chalcocite occur in the upper and more central parts. The boundary between bornite–chalcocite mineralisation and chalcopyrite mineralisation (the bornite–chalcopyrite interface) is usually sharp (Reeve & others, 1990). This boundary forms a convoluted surface which generally dips downwards towards the boundary of the central hematite–quartz breccia. Grades of 4% to 6% Cu are common in the bornite–chalcocite zones, whereas the chalcopyrite zones are usually less than 3% Cu (Reeve & others, 1990). Ore textures show that much of the copper sulphide mineralisation either post-dates or is coeval with the hematite (Cross & others, 1993).

Uranium mineralisation occurs within heterolithic hematitic breccias and hematite breccias as disseminations, microveinlets and aggregates of fine-grained pitchblende intergrown with copper sulphides. Pitchblende also forms small aggregates which are intergrown with or replace breccia material. Small amounts of coffinite and brannerite[1] are closely associated with pitchblende. Narrow, higher-grade uranium zones often occur in the bornite–chalcocite zones, especially with hematite breccias (Cross & others, 1993). Some high-grade zones of uranium mineralisation transgress the bornite–chalcopyrite interface.

Gold and silver mineralisation occurs mostly as fine-grained disseminations either within, or closely associated with copper sulphide minerals.

The mineralised hematite breccias commonly contain approximately 0.2% La and 0.3% Ce. The most abundant rare earth element minerals are bastnaesite and florencite, which are fine-grained and commonly intergrown with hematite and sericite (Oreskes & Einaudi, 1990).

Genesis

The genesis of the Olympic Dam deposit has been described by many authors including Reeve and others (1990), Johnson and Cross (1991, 1995), Oreskes and Einaudi (1992), Cross and others (1993), Smith (1993) and Haynes and others (1995). The deposit formed as part of a large hydrothermal breccia complex. Much of the brecciation occurred in a near surface environment where phreatic and phreatomagmatic activity formed a large eruption crater in which hydrothermal eruption breccias and subaerial pyroclastics accumulated. The breccia complex and the deposit experienced a long history of episodic faulting. Precipitation of metals was probably due to redox reactions resulting from the mixing of ascending, hot, reduced, Fe-rich waters with cooler meteoric and/or lacustrinal waters occupying the near surface parts of the breccia complex (Cross & others, 1993; Haynes & others, 1995). The meteoric and lacustrine waters were oxidising, and were derived from a provenance containing mafic volcanic rocks. The groundwater was probably responsible for transport of Cu, U, Au and most of the S into the breccia complex, where it reacted with the hotter water which introduced most of the Fe, F, Ba and CO_2 from below. The huge size of the orebody reflects the persistence of fluid-mixing events over a focused heat source beneath, or adjacent to, a saline playa lake in a volcanic setting.

Geological evidence presented by Reeve and others (1990) together with U–Pb isotopic age dating (Creaser & Cooper, 1993; Johnson & Cross, 1995) suggest that introduction and deposition of ore metals occurred at the same time as the formation of the hematite breccias. The U–Pb zircon dates for rocks within the breccia complex and the diatreme indicate that the ODBC formed at ~1590 Ma, and that brecciation closely followed emplacement and cooling of the Roxby Downs Granite. Mineralisation was introduced during formation of the hematite breccias at ~1590 Ma (Johnson & Cross, 1995).

[1] Appendix 4 gives the chemical compositions of uranium minerals.

The Olympic Dam deposit is closely related to Gawler Range volcanics–Hiltaba Suite volcanic and plutonic activity. Ore was precipitated in an active hydrothermal system penecontemporaneously with emplacement of high-level extrusives and intrusives. The U–Pb ages of these rocks are indistinguishable from the ages of Gawler Range Volcanics elsewhere and from the host Roxby Downs Granite (Johnson & Cross, 1991, 1995).

Resources

The Olympic Dam copper–uranium–gold–silver deposit is the world's largest deposit of low-cost uranium. The ore reserves and mineral resources as at December 1999 are shown in Table 8 (WMC, 1999).

Table 8. Olympic Dam ore reserves and mineral resources as at December 2000 (WMC, 2000)

		Mt	Cu %	Au g/t	U_3O_8 %	U_3O_8 (t)
Reserves	Proved	122	2.4	0.6	0.06	*732 000
	Probable	586	1.6	0.5	0.05	*293 000
Resources	Measured	560	1.7	0.5	0.05	280 000
	Indicated	1310	1.2	0.5	0.04	524 000
	Inferred	640	1.1	0.4	0.03	192 000
Total Resources		2510	1.3	0.5	0.04	996 000

* These are included in the resources figures.

Other Cu–U–Au prospects in the Stuart Shelf area of Gawler Craton

Sub-economic Cu–U–Au mineralisation in hematite or magnetite-rich breccias has been intersected at the Acropolis, Wirrda Well, Oak Dam and Emmie Bluff prospects (Fig. 6). **Acropolis** and **Wirrda Well**[2] are approximately 25 km south-west and 25 km south-south-east respectively, from Olympic Dam. The Stuart Shelf sediments overlying basement rocks at Acropolis and Wirrda Well have minimum thicknesses of 480 m and 330 m, respectively, and the significant zones of Cu–U–Au mineralisation occur tens to hundreds of metres below the unconformity at the base of these sediments (Cross, 1993).

At Acropolis, mineralisation occurs in a magnetite and hematite-rich vein system, and in alteration zones within Gawler Range Volcanics. At Wirrda Well, mineralisation is within hematite-rich granitic breccias (in Burgoyne Batholith) similar to the Olympic Dam deposit. Uranium and rare earth elements mineralisation at the **Oak Dam** prospect, 70 km south-east of Olympic Dam, is in hematite breccia, conglomerate and siltstone (Parker, 1990). Mineralisation at **Emmie Bluff** prospect, 75 km south-south-east of Olympic Dam, is in hematite-rich zones associated with faulted Wandearah metasiltstone.

At the **Alford** prospect, 10 km north-east of Wallaroo on the northern part of Yorke Peninsula, Cu–Au–Mo and minor U mineralisation is hosted by Wandearah Metasiltstone and Doora Schist adjacent to the Hiltaba age equivalent Tickera Granite (~ 1600 to 1570 Ma). The Tickera granites show local endoskarn-like alteration to calc-silicate, alkali feldspar and magnetite metasomatites (Curtis, Vanderstelt & Parker, 1993; Daly & others, 1998).

[2] From now on, the names of uranium prospects are in bold font on first specific occurrence in the text.

MOUNT PAINTER FIELD

Small high-grade veins of secondary uranium mineralisation (mainly torbernite and autunite) at Radium Ridge were mined intermittently between 1910 and 1932. The ore concentrate was treated to extract radium for medical use.

From 1944 to 1950, exploration by the South Australian Department of Mines outlined several million tonnes of low-grade uranium–rare earth elements mineralisation at the East Painter deposit, 2 km east of Mount Painter (Dickinson, Wade & Webb, 1954).

Between 1968 and 1971, the Exoil–Transoil partnership completed a major exploration and drilling program over a large area of the Mount Painter Inlier. This work outlined several small uranium deposits.

From 1990 to 1994, CRA Exploration Pty Ltd carried out detailed aeromagnetic and radiometric surveys, stream sediment sampling and diamond drilling in the Mount Gee–Mount Painter area to explore for uranium. Drilling outlined a large body of low-grade uranium mineralisation at the Mount Gee East prospect (Louwrens, 1992).

Regional geological setting

The oldest rocks of the Mount Painter Inlier (see Fig. 26) are a sequence of Palaeoproterozoic meta-pelites, schists, calc-silicates and quartzites called the 'Radium Creek Metamorphics'. During the Mesoproterozoic there were two phases of granitoid intrusion, volcanics and metasediments (Robertson & others, 1998). These Mesoproterozoic granitoids and metamorphics form most of the Mount Painter Inlier. Cambrian-Ordovician age granitoids intrude older basement rocks of the Inlier.

The **Radium Ridge Breccias** occur in the south-central part of the Inlier. There are several large bodies of breccia ranging in area from a few hundred square metres to 3 km^2 and these occupy a total area of 7 km^2. The breccias are associated with a major fault system. Three major types of breccia have been identified: *granitic breccia*, *hematitic breccia* and *chloritic breccia* (Drexel & Major, 1990). *Granitic breccia* is by far the most common lithology. The breccia clasts and finer grained matrix are locally derived granite, gneisses and schists of the Mount Painter Complex. In places the breccias show bedding and other sedimentary structures. Potassium metasomatism and silicification have partly to completely replaced portions of the breccia. *Hematitic breccias* form lens-shaped bodies, up to 68 m thick, which occur at or near the base of the breccia pile. Hematite forms the matrix and the clasts are granitic material, partially replaced by hematite in places. In some areas there is a gradation from granitic breccia to hematitic breccia (Louwrens, 1991). In places the granitic breccias and hematitic breccias have been extensively chloritised to form *chloritic breccia*.

The **Mount Gee Sinter** (Drexel & Major, 1990) is an epithermal quartz–hematite layered sequence which overlies the Radium Ridge Breccias and adjacent basement.

The Radium Ridge Breccias appear to have formed by both hydrothermal and sedimentary processes. Parts of the breccia sequence are interpreted to have formed from in situ brecciation of the basement rocks caused by an Early Palaeozoic near-surface hydromagmatic event associated with the 'younger granite suite' (Drexel, 1980; Lambert & others, 1982). Hydraulic fracturing along pre-existing crustal weaknesses was probably the main cause of brecciation. Hematite was introduced during hot spring activity which also formed the Mount Gee Sinter. Other areas of breccia contain interbedded sediments and these breccias are probably sedimentary in origin. Drexel and Major (1990) concluded from the regional geology and other evidence that the Radium Ridge Breccias are Late Ordovician to Silurian in age.

From a study of the palaeomagnetism within the breccias, and age dating of monazite samples, Idnurm and Heinrich (1993) proposed a Permo-Carboniferous age for the hydrothermal activity and uranium mineralisation. However, these authors also added that, from the available data, they could not exclude the possibility that the uranium mineralisation may be older and may initially have formed concentrations in ironstone formations. Neumann and others (2000) noted extreme concentrations of uranium, thorium and potassium within Mount Painter granites and added that the Th:U ratios for these suites are dominantly 3 to 5, suggesting that extreme enrichment is a primary magmatic feature. The uranium-enriched granites have been dated at 1575 Ma and 1555 Ma, which may represent a maximum age-limit for the uranium mineralisation (Wyborn & others, 1992).

Geochemical data from the analyses of 60 samples of hematite breccia show that these breccias are enriched in uranium (average 0.066% U), rare earth elements (average 0.61% Ce) and copper (average 0.11% Cu) (Drexel & Major, 1990).

Neoproterozioc sediments of the Adelaide Geosyncline unconformably overlie rocks of the Mount Painter Complex to the west.

Mount Gee/Mount Gee East deposit

In the Mount Gee area, an extensive sheet of hematite breccia and hematite-rich granitic breccia contains widespread low-grade uranium–rare earth elements–copper mineralisation. Drilling by Exoil–Transoil in the late 1960s defined a small near-surface uranium deposit (2 721 600 t ore at 0.1% U_3O_8, containing 2722 t U_3O_8). Drilling carried out by CRA Exploration Pty Ltd (from 1990 to 1994) and later by Goldstream Mining NL (from 1999 onwards) outlined a large body of low-grade uranium mineralisation which appears to be a down-faulted extension of the near-surface zone. This new zone, which CRA referred to as the **Mount Gee East** prospect (Louwrens, 1992) is approximately 120 m below surface.

Recent drilling together with results from re-assaying of core from old holes drilled by Exoil has shown that the zone of uranium mineralisation extends over a strike length of more than 250 m and is open along strike in both directions. Mineralisation assaying more than 0.1% U_3O_8 occurs over widths of 25–100 m and the zone is from 10 to 50 m thick (Goldstream, 1999, 2000). The zone also contains approximately 0.5% rare earth elements (Ce, La), 0.1% Cu and 1 g/t Ag.

Re-assaying of the old drill core has identified many zones of mineralisation which had not been assayed by Exoil–Transoil because these companies used scintillometers to identify the mineralised zones in drill core (Goldstream, 2000).

Other deposits

A number of other small uranium–rare earth deposits occur in hematitic breccias in an area of 30 km^2 surrounding Mount Painter and Mount Gee. Uraninite mineralisation is associated with hematite and chlorite, plus minor fluorite, barite and manganese oxides. The main deposits are Radium Ridge, Armchair-Streitberg, Hodgkinson, Gunsight and Shamrock (Fig. 26). The Hodgkinson deposit is hosted by granitic breccia. Hematite and chlorite are absent. These are considered to be breccia-complex-type deposits because of similarities in breccia occurrence and mineralisation between the Radium Ridge Breccias and the much older Olympic Dam deposit (Youles, 1984, 1986; Drexel & Major, 1987) which is Mesoproterozoic in age.

In 1970, the Exoil–Transoil partnership announced the following ore reserves, using a cut-off grade of 0.05% U_3O_8:

- **Radium Ridge** — 3 628 800 t ore at 0.06% U_3O_8, containing 2177 t U_3O_8;

- **Armchair-Streitberg** — 1 814 400 t ore at 0.1% U_3O_8, containing 1814 t U_3O_8;
- **Hodgkinson** — 226 800 t ore at 0.25% U_3O_8, containing 567 t U_3O_8.

At the **Gunsight** prospect, 40 km north-east of Mount Painter, uranium is associated with copper, cobalt and rare earth elements. The host rocks are pelites and acid volcanics that are part of the Brindana Schist sequence of the Radium Creek Metamorphics.

At the **Shamrock** copper mine, 10 km north of Mount Painter, pitchblende has been identified in the copper deposits which occur in shear zones in Neoproterozoic sedimentary rocks next to the Mount Painter Complex.

UNCONFORMITY-RELATED DEPOSITS

In Australia, unconformity-related deposits and occurrences are located in the Northern Territory, Western Australia and South Australia. The Pine Creek Inlier in Northern Territory contains the world-class unconformity-related uranium deposits in the Alligator Rivers field, as well as the Rum Jungle and South Alligator Valley fields. Other unconformity-related uranium deposits are present in the Rudall Complex (WA) and in the Turee Creek area (WA). Minor unconformity-related uranium occurrences are present in the Granites–Tanami Inlier (WA and NT), Halls Creek area (WA), Tennant Creek area (NT) and Eyre Peninsula (SA).

ALLIGATOR RIVERS URANIUM FIELD

The Alligator Rivers uranium field is in the Pine Creek Inlier (Figs 9 and 10) about 220 km east of Darwin (NT). It contains the major uranium deposits at Ranger 1, Koongarra, Jabiluka and Nabarlek. Koongarra, Ranger 1 and Jabiluka are enclosed by the Kakadu National Park, although the immediate areas around each of these deposits were excluded from the park when it was proclaimed. Nabarlek is in the Arnhem Land Aboriginal Reserve.

The mineral potential of the area was recognised in 1967, when BMR published a revised 1:500 000 geological map of the Darwin–Katherine region which showed probable Archaean basement in the Alligator Rivers area. The Archaean rocks were shown to be unconformably overlain by deformed and metamorphosed Palaeoproterozoic strata which were in turn overlain by Mesoproterozoic sandstones of the McArthur Basin. This map highlighted similarities to the uranium deposits in the Archaean–Palaeoproterozoic–Mesoproterozoic setting at Rum Jungle. Recent investigations have indicated that the cover sandstones in the Alligator Rivers area are of late Palaeoproterozoic rather than Mesoproterozoic age (Sweet, Brakel & Carson, 1999).

The Ranger 1 deposits were detected as a very strong anomaly in an airborne radiometric survey in 1969. Koongarra was represented as a more subtle anomaly in the same survey and was discovered in the course of a ground follow-up in 1970. Nabarlek was detected as an intense anomaly in an airborne radiometric survey in 1970. The Jabiluka 1 deposit was discovered in 1971 during the investigation of a very weak ground surface radiometric anomaly, and Jabiluka 2 was found in 1973 by drilling along strike from Jabiluka 1.

The proposed development of the Ranger 1 deposits became the subject of an Environmental Inquiry conducted by the Fox Commission under the *Environmental Protection (Impact of Proposals) Act 1974*. The Fox Commission issued its first report in October 1976 and a second report in May 1977. In August 1977 the Commonwealth Government announced its decision to allow the development of Ranger 1 subject to various conditions.

Regional geological setting

The Alligator Rivers uranium field is in the north-eastern part of the Pine Creek Inlier (Figs 9 and 10). The regional metamorphic grade (mainly amphibolite facies) and degree of deformation in this area are markedly greater than elsewhere in the inlier (Needham & Stuart-Smith, 1980; Needham, 1988b). In the western part of the field, Palaeoproterozoic metasediments overlie and grade into Archaean–Palaeoproterozoic granitoids of the Nanambu Complex dated at 2500 Ma (Page, Compston & Needham, 1980; Needham & De Ross, 1990). In the north-east, the Myra Falls Metamorphics adjoin the tonalites and migmatites of the Palaeoproterozoic Nimbuwah Complex. All these rocks were intensely folded and metamorphosed between 1870 Ma and 1855 Ma during the main period of faulting, folding and metamorphism of the Nimbuwah Event which is part of the 1880–1850 Ma Barramundi Orogeny

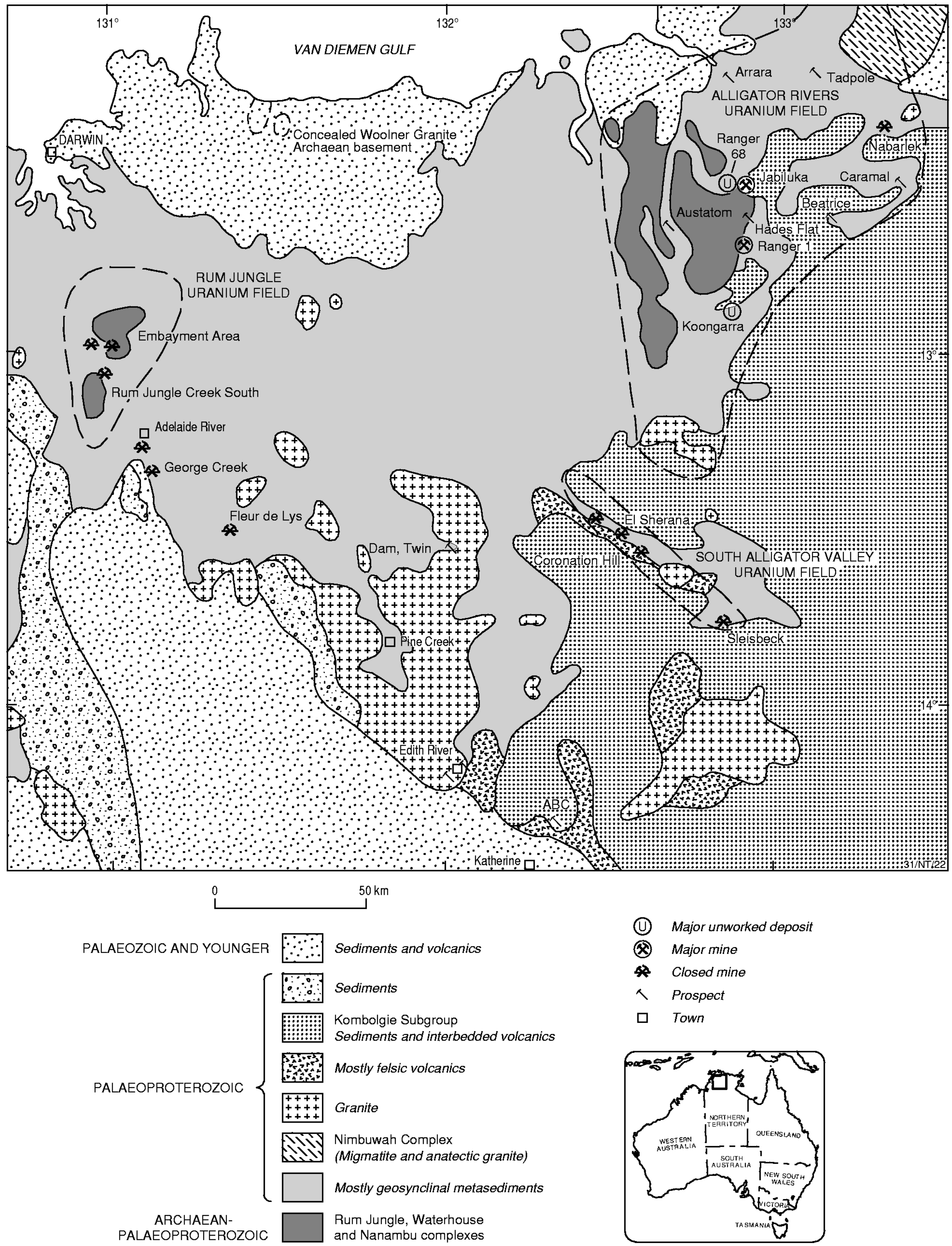

Figure 9. Generalised regional geology, Pine Creek Inlier, showing uranium fields, deposits and prospects

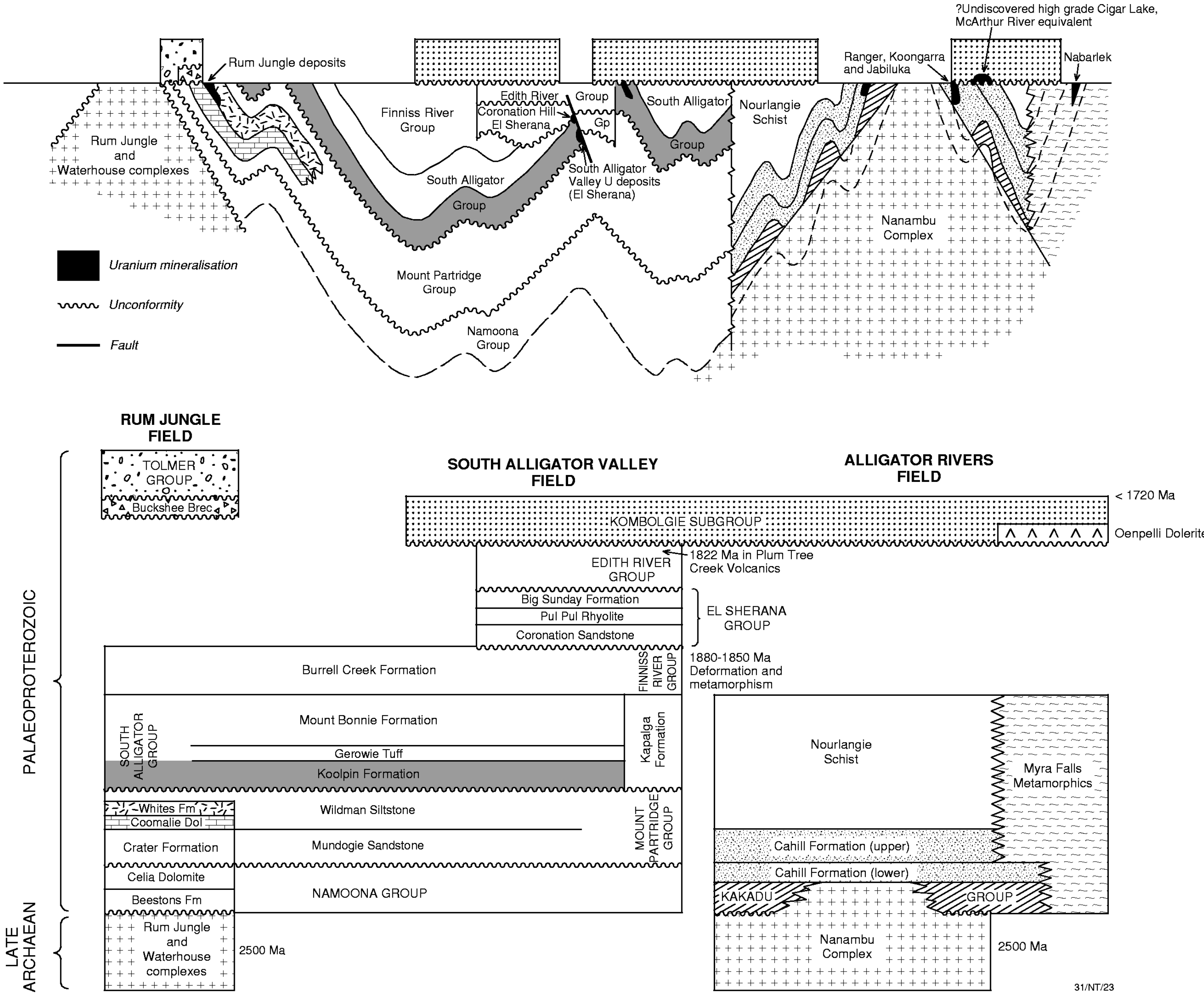

Figure 10. Schematic diagram of relationships between uranium mineralisation, favourable host rocks and Palaeoproterozoic unconformity in the Pine Creek Inlier. The diagram does not fully represent the stratigraphy, but shows the relationships between units significant in describing the uranium mineralisation. Igneous rocks other than basement units have been omitted.

(Needham, 1988b). Over most of the field the metamorphism reached amphibolite grade, while in parts of the Nimbuwah Complex it reached granulite grade. East of the East Alligator River the Palaeoproterozoic metasediments grade into schists and gneisses of the Myra Falls Metamorphics.

Before being deformed and metamorphosed, the Palaeoproterozoic sediments were intruded by tholeiitic dolerite sills (Zamu Dolerite), and after deformation ceased the metasediments were intruded by small granitic stocks.

The Palaeoproterozoic metasediments are unconformably overlain by the late Palaeoproterozoic Kombolgie Subgroup, of the Katherine River Group, which consists of a thick sequence of sandstones (200–1000 m thick) with interbedded andesitic volcanics. The Jimbu Microgranite intrudes the upper part of the Katherine River Group and has a SHRIMP U–Pb age of 1720 ± 7 Ma (Rawlings, 1999; Rawlings & Page, 1999). The Plum Tree Creek Volcanics, below the unconformity at the base of the Kombolgie Subgroup, have yielded a SHRIMP U–Pb age of 1822 ± 6 Ma (R.W. Page, quoted in Kruse & others, 1994). The age of the Kombolgie Subgroup is thus constrained between 1822 Ma and 1720 Ma.

The Ranger 1, Jabiluka and Koongarra deposits and most of the significant uranium prospects are in the lower member of the Palaeoproterozoic Cahill Formation and occur adjacent to the Nanambu Complex (Needham & Stuart-Smith, 1980). The lower member of the Cahill Formation is characterised by the presence of metamorphosed carbonate rocks and includes interlayered mica schist, chloritised feldspathic quartzite, quartz schist, para-amphibolite and calc-silicate rock. The Nabarlek deposit is hosted by Myra Falls Metamorphics, which may be metamorphosed equivalents of the lower member of the Cahill Formation.

The uranium deposits post-date the main period of regional metamorphism. The U–Pb isotope age-dating studies have indicated a 1737 ± 20 Ma age for mineralisation at Ranger, while Jabiluka mineralisation has recorded ages of 1437 ± 40 Ma (Ludwig & others, 1987). The Sm–Nd ages for mineralisation at the Jabiluka 2, Nabarlek and Koongarra deposits are all in the range 1600–1650 Ma (Maas, 1989). These authors concluded that Ranger mineralisation is significantly older than the other deposits and considered that it is older than the overlying Kombolgie Subgroup. More recent regional mapping and SHRIMP age dating constrains the age of the Kombolgie Subgroup to 1720–1822 Ma, bracketing it with the U–Pb age of the pitchblende at Ranger. As far as the Jabiluka deposit is concerned, it is not clear whether there was an extended period (about 20 million years) of ore formation starting at around 1600 Ma, or whether post ore disturbance caused a wide spread of isotope ages (Hancock, Maas & Wilde, 1990).

Geological features

Features associated with some of the unconformity-related uranium deposits in the Alligator Rivers, Rum Jungle and South Alligator Valley uranium fields are as follows (modified after Ewers & others, 1984; Mernagh, Wyborn & Jagodzinski, 1998):

- the host rocks occur in intracontinental or continental margin basins;
- the deposits are near to a late Palaeoproterozoic oxidised thick cover sequence (>1 km) of quartz-rich sandstone;
- the basement is chemically reduced, containing carbonaceous/ferrous iron-rich units or feldspar-bearing rocks;
- the deposits are associated with a Palaeoproterozoic/late Palaeoproterozoic unconformity and with dilatant brecciated fault structures, which cut both the cover and basement sequences and separate reduced lithologies from the oxidised cover sequence;

- most of the large deposits in the Alligator Rivers and the Rum Jungle fields are in stratabound ore zones and have a regional association with carbonate rock/pelitic rock contact, but an antipathetic relationship with carbonate in the ore zones;
- the major Australian deposits lie close to an unconformity although the Jabiluka deposit is still open some 550 m below the unconformity;
- the known major uranium deposits are present where the oxidised cover sequence is in direct contact with the reducing environments in the underlying pre-1870 Ma Archaean–Palaeoproterozoic basement and not separated by an intervening sequence, as by the El Sherana and Edith River Groups in the South Alligator Valley uranium field;
- unlike the Cigar Lake and McArthur River deposits in the Athabasca Basin (Canada), in Australia there is an absence of extensive mineralisation in the cover rocks at the Jabiluka 2 deposit, despite the local abundance of chloritised zones; the cover sandstone has been eroded away from the other sites of major uranium deposits in the Alligator Rivers and the Rum Jungle uranium fields;
- the major deposits are older than 500 Ma with the majority between 1350 Ma and 1750 Ma;
- in the Alligator Rivers and Rum Jungle fields, the proximity to the Archaean–Palaeoproterozoic complexes appears significant.

Alteration

Alteration features associated with the deposits are:

- alteration extends over 1 km from the deposits,
- alteration is characterised by sericite–chlorite ± kaolinite ± hematite,
- Mg metasomatism and the formation of late-stage Mg rich chlorite are common,
- strong desilicification occurs at the unconformity.

Source of uranium mineralisation

Archaean and Palaeoproterozoic granites of the Alligator Rivers and South Alligator Valley uranium fields have uranium contents which are well above the crustal average of 2.8 ppm U (Wyborn, 1990a). Granites and granitic gneisses of the Nanambu complex contain 3–50 ppm U; tonalites, granitic gneisses and granitic migmatites of the Nimbuwah complex have 1–10 ppm U. The Nabarlek Granite that has been intersected in drill holes below the Nabarlek deposit has 3–30 ppm U, and the Tin Camp and Jim Jim Granites also have high uranium contents. The Malone Creek Granite (South Alligator Valley) has 11–28 ppm U. Wyborn (1990b) suggested that the underlying crust in the region of these uranium fields is enriched in uranium.

Maas (1989) concluded from Nd–Sr isotopic studies that for Jabiluka, Nabarlek and Koongarra, the uranium was derived from two sources: the Palaeoproterozoic metasediments and a post-unconformity source, probably highly altered volcanics within the Kombolgie Subgroup. Maas (1989) also proposed that these orebodies formed when hot oxidising meteoric waters, which contained uranium derived from volcano-sedimentary units within the Kombolgie, reacted with reducing metasediments of the Palaeoproterozoic basement.

Formation of unconformity-related uranium deposits

Dahlkamp (1993), Ruzicka (1995) and Mernagh and others (1998) have summarised the various mechanisms that have been proposed to explain the origin (including source, transport and formation) of unconformity-related uranium deposits in Australia and in the Athabasca Basin, Canada.

Ore formation after the deposition of the cover sandstones

Two models are proposed for ore formation after the cover sandstones were deposited:

- the *meteoric model* (Johnston & Wall, 1984; Wilde, Bloom & Wall, 1989a; Jaireth, 1992; Mernagh & others, 1994; Solomon & Groves, 1994; Komninou & Sverjensky, 1996), which proposes that highly oxidised acidic and Ca-rich meteoric brine in a neutral cover sequence flowed down faults and dilational structures. Mixing with reduced fluids from below the unconformity, or direct interaction with carbonaceous or other strongly reduced basement lithologies, caused precipitation of U as well as Au + platinum group elements (PGE). Fluid interaction with feldspathic or calcareous rocks caused only a moderate increase in pH and a decrease in the oxidation state (fO_2), leading to precipitation of Au and PGE, but little or no precipitation of U (e.g. Coronation Hill deposit).
- the *diagenetic model*, which was developed by Hoeve and others (1980), Sibbald and Quirt (1987) and Ruzicka (1993) for the unconformity-related deposits in the Athabasca Basin. Hancock and others (1990) considered that a similar model may be applicable to Jabiluka. According to these authors, oxidised ore-bearing fluids formed within the sedimentary cover during high-temperature prograde diagenesis. Some of the fluids entered the basement and were reduced before ascending again along faults and fractures, where they mixed with laterally moving oxidised fluids. Precipitation of U and other metals took place at the interface between the oxidising and reducing fluids (i.e. at the redox front). High-grade uranium or polymetallic mineralisation formed directly at or slightly above the unconformity (e.g. Cigar Lake, McArthur River (Canada)). Medium-grade uranium mineralisation may have formed below the unconformity (e.g. Rabbit Lake (Canada), Jabiluka) and low-grade uranium mineralisation may have formed some distance above the unconformity (e.g. Maurice Bay (Canada)). The Cigar Lake-style high-grade unconformity-related deposits at the unconformity have not been found in the Pine Creek Inlier to date although such deposits could be completely concealed by the cover sandstones.

Ore formation prior to the deposition of cover sandstones

Recent mapping and age dating suggest that the cover sandstones of the overlying Kombolgie Subgroup must be older than 1720 Ma and may be 1750 Ma or older (Sweet & others, 1999). These cover sandstones are older than the Jabiluka, Koongarra and Nabarlek deposits and may also predate the Ranger deposit (1737 ± 20 Ma). It is still possible that the Ranger deposit is older, in which case it may be possible that at least part of the uranium mineralisation commenced shortly before the deposition of the overlying sandstones and continued as the sandstones were being deposited. There are two models that describe this.

- The *supergene model* has been put forward, in several versions, by Knipping (1974), Ruzicka (1975), Crick and Muir (1980), Donnelly and Ferguson (1980), Ferguson, Ewers and Donnelly (1980), Ewers and others (1984) and Needham (1988b). Proposals by these authors include syngenetic enrichment of uranium in the pre-1870 Ma sediments, followed by supergene enrichment. Subsequent to the regional metamorphism a prolonged period of erosion and weathering imposed a saprolitic profile as much as 100 m deep, and peneplaned the early Palaeoproterozoic rocks. Uranium and other metals were leached from Palaeoproterozoic rocks and the weathering-profile by surface waters, and precipitated in reducing environments. Breccia ore zones at Ranger and Jabiluka formed in carbonate-rich sequences during peneplanation of the Palaeoproterozoic strata and before the cover rocks were deposited. Downward-percolating meteoric waters transporting uranyl complexes were met by reducing conditions in breccia zones where uranium oxide was precipitated. It is presumed that this happened during formation of the regolith at the unconformity and before the deposition of the cover sandstones. Maas (1989) noted that Sr and Nd found in uranium ores from Nabarlek, Jabiluka and possibly Koongarra are isotopically sufficiently different from measured isotope signatures in both the late Archaean and the Nabarlek Granite to render these rock types the most unlikely uranium source rocks. Maas (1989) also argued that his data did not support derivation of radiogenic Nd from remobilisation of pre-Kombolgie concentrations of colluvial uranium.

- The *hypogene model* has been proposed by Hegge & Rowntree (1978) and Binns, McAndrew and Sun (1980). Heat generated from adjacent granites drove a convective cell of metalliferous fluids. The source of the fluids is considered to have been deep-seated and generated during the metamorphic event preceding deposition of the overlying sediments. Ludwig and others (1987) proposed that the first high-grade concentration took place after the peak of regional metamorphism but at a time when early postmetamorphic igneous bodies were still being emplaced. However, recent studies suggest that these igneous bodies are older. Some of the high-grade mineralisation may be an enrichment of earlier low-grade syngenetic concentrations in the lower Cahill Formation. This model cannot satisfactorily account for the spatial association of mineralisation with the unconformity between basement and overlying sediments.

Ranger 1 — No. 1 Orebody, No. 3 Orebody

After the initial discovery in 1969, Geopeko Ltd outlined intense radiometric anomalies over the Ranger 1 deposits over a strike length of about 6 km (Fig. 11) (Ryan, 1972). By the end of 1970 at least two viable orebodies — Orebodies 1 and 3 — had been outlined by drilling of the more significant anomalies (Eupene, Fee & Colville, 1975).

The Ranger 1 deposits are in the lower member of the Cahill Formation on the eastern side of the Nanambu Complex. In ascending stratigraphic order (Fig. 12) the Footwall Sequence is correlated with the Nanambu Complex, the Lower and Upper Mine Sequences with the lower member of the Cahill Formation, and the Hangingwall Sequence with part of the upper member of the Cahill Formation. In the Ranger 1 area the metasediments strike northerly and dip east at varying angles.

Most of the ore in No. 1 Orebody (mined out) and No. 3 Orebody (Fig. 12) is in the Upper Mine Sequence, which is mainly chloritised biotite–quartz–feldspar schist and microgneiss with thin carbonaceous lenses (Eupene & others, 1975). Both orebodies also extend into the Lower Mine Sequence, which is mainly recrystallised magnesian or dolomitic marble, chloritic in the upper part. The No. 1 Orebody extended roughly 500 m along strike and about 300 m across strike. It was confined to a discrete basin-shaped structure (breccia zone) formed by thinning of the chloritic carbonate unit immediately below the orebody and thrusting of the mine sequence rocks over the basement sequence (Kendall, 1990). Within the No. 1 and No. 3 Orebodies there are many low-angle faults which dip 15–20°E. These small faults are discontinuous and overall they show a westward movement (Kendall, 1990). The No. 1 Orebody and No. 3 Orebody are broadly conformable with the host rocks (Fig. 12) — they strike north–south, with an overall dip to the east. Within the ore zone there were several periods of brecciation with associated chloritisation and remobilisation of uranium mineralisation. According to Ludwig and others (1987) and Maas (1989), the initial mineralisation may have pre-dated the deposition of the Kombolgie Subgroup while the later period of remobilisation of mineralisation post-dates the Kombolgie (Page & others, 1980). However, recent work suggests that the age of the Kombolgie Subgroup lies between 1720 Ma and 1822 Ma (Sweet & others, 1999) and the deposition of the Kombolgie sandstones may have commenced before the formation of the Ranger deposit.

A large block of chloritised Kombolgie sandstone occurs on the western side of No. 3 Orebody. A blind deposit occurs in carbonates of the Lower Mine Sequence east of No. 3 Orebody, about 250 m below the surface and is associated with localised chloritisation. The average grade of this blind deposit is 0.1% U_3O_8.

Both the Upper and Lower Mine Sequences are severely brecciated in the ore zones and extensively invaded by chlorite veins, which carry most of the mineralisation (Hegge & others, 1980). A distinctive thin band with characteristic chlorite lenticles forms an important marker horizon (Eupene & others, 1975). Within the No. 3 Orebody there is little evidence of massive dissolution of the carbonate.

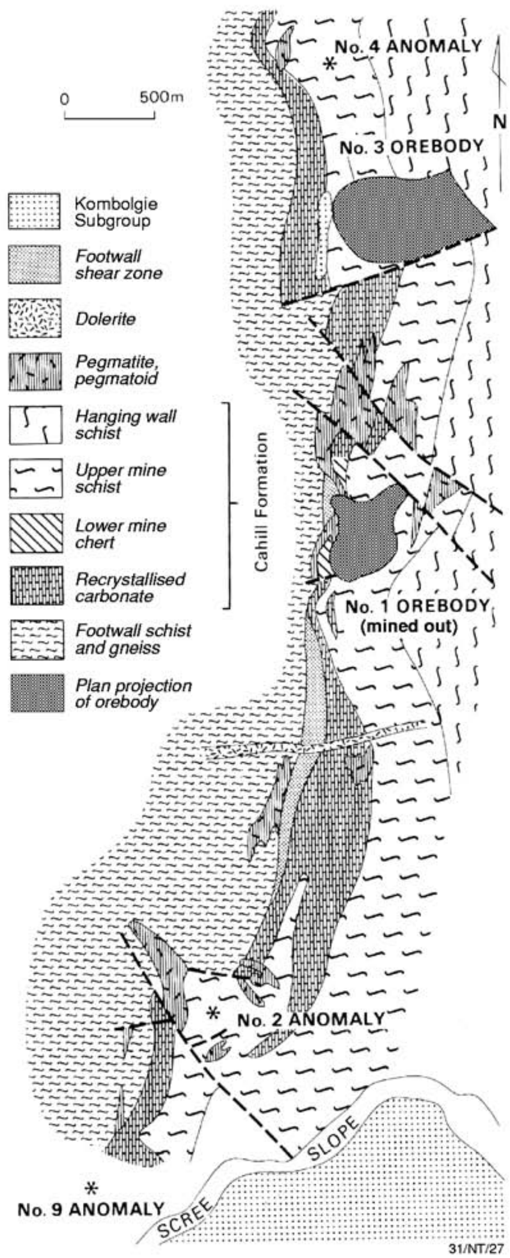

Figure 11. Generalised geological plan of Ranger 1 orebodies and prospects (from Needham, 1982a, after Eupene & others, 1975, and Hegge & others, 1980)

The primary ore consists of uraninite with minor brannerite and amorphous mixtures of uranium oxides (pitchblende) with titanium and phosphates. Thucholite was reported from the No. 3 Orebody. Gangue minerals associated with the pitchblende mineralisation are chlorite, quartz, titanium oxides, hematite, apatite, pyrite, chalcopyrite and galena (predominantly radiogenic).

Resources

The total size of the No. 1 Orebody prior to the commencement of mining was calculated, using a cut-off grade of 0.05% U_3O_8, to be 22.159 Mt averaging 0.259% U_3O_8, which contained 57 392 t U_3O_8. The total size of the orebody, calculated using a cut-off grade of 0.1% U_3O_8, was 15.870 Mt averaging 0.333%

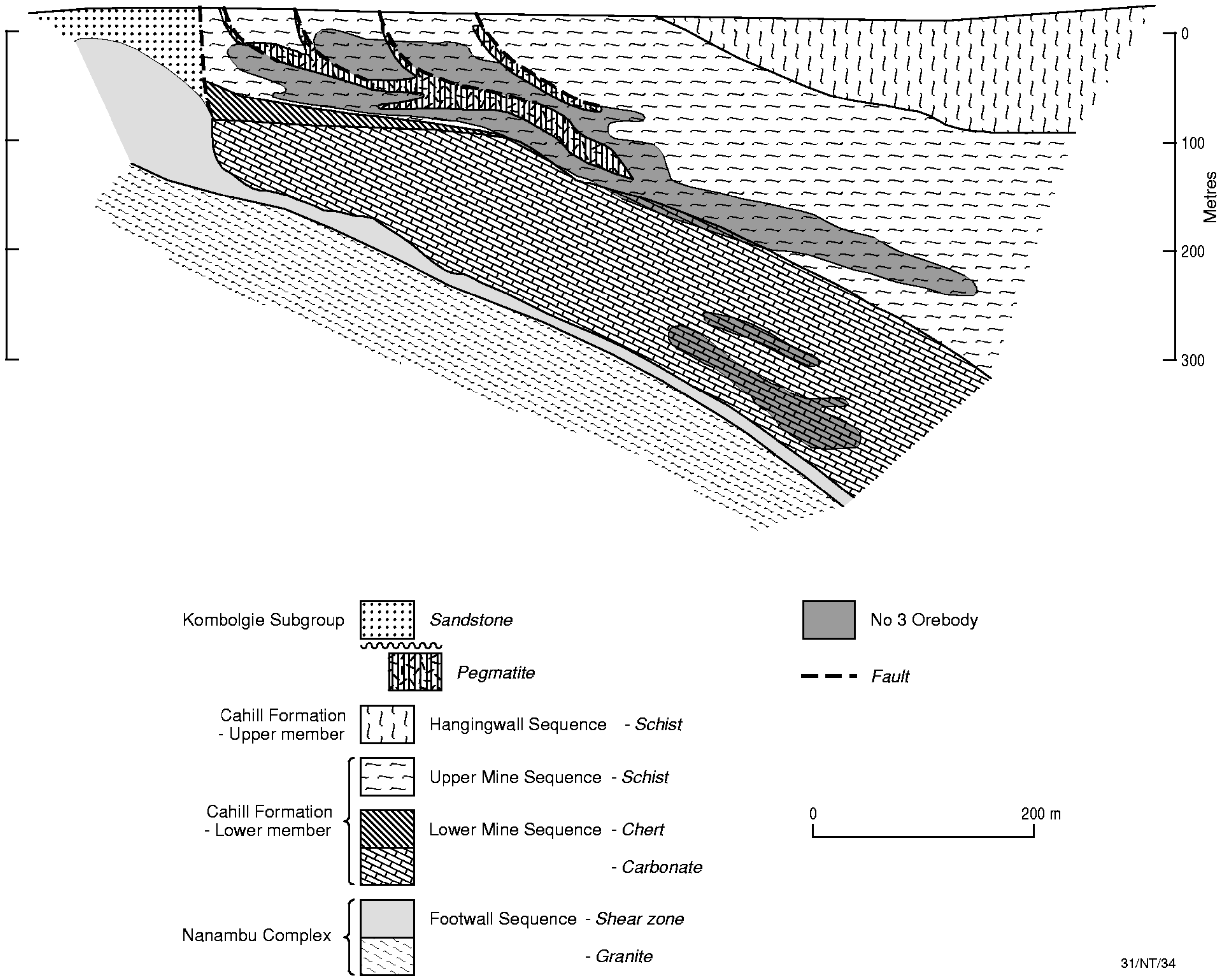

Figure 12. Schematic E–W cross-section, Ranger 1 No. 3 Orebody (L Hughes, Energy Resources of Australia Pty Ltd, December 1999)

U_3O_8, which contained 52 878 t U_3O_8 (ERA Ltd, 1980). A total of 19.78 Mt ore averaging 0.32% U_3O_8 was mined from the No. 1 open cut. Milling of this ore produced a total of 55 000 t U_3O_8 (ERA Ltd Geological staff pers comm.).

The uranium ore reserves and mineral resources for No. 3 Orebody as at June 2000 are shown in Table 9. Within the No. 3 Orebody there is a narrow (2–3 m thick) zone of high grade ore up to 8% U_3O_8 against the contact between chert and Upper Mine Sequence, associated with intense brecciation. Above this zone in the Upper Mine Sequence there is a wider zone of weakly brecciated, chloritised schist hosting mineralisation which averages 0.15% U_3O_8.

Gold values within No. 1 Orebody averaged just over 1 g/t in areas of high-grade uranium mineralisation, and are up to 0.5 g/t throughout the lower grade areas. In No. 3 Orebody, gold values are generally less than 0.5 g/t (Kendall, 1990).

Ranger 1 — Anomalies 2, 4 and 9

Anomalies 2 and 9 of the Ranger 1 group are approximately 3 km south of the No. 1 Orebody (Fig. 11). Anomaly 2 was extensively auger- and percussion-drilled. Hegge and others (1980) stated that there was

Table 9. Ore reserves and mineral resources for Ranger No. 3 Orebody as at June 2000, calculated at a cut-off grade of 0.12% U_3O_8 (ERA Ltd, 2000)

Ranger No. 3 Orebody	Mt	Grade % U_3O_8	U_3O_8 (t)
Stockpile	7.1	0.19	13 843
Proved plus probable ore reserves	14.9	0.29	43 483
Measured plus indicated mineral resources*	21.6	0.26	57 000
Inferred resources	12.4	0.19	23 251
Total resources	34.0	0.24	80 251

* Mineral resources are inclusive of those resources modified to produce ore reserves

every chance of establishing a mineable resource. The uranium is in carbonaceous and chloritic schist near the base of the Upper Mine Sequence. Secondary uranium mineralisation was also intersected in the Upper Mine Sequence at Anomaly 9. Anomalies 2 and 9 were excluded from the Ranger 1 Project Area as recommended by the Ranger Uranium Environmental Inquiry. At Anomaly 4, about 800 m north-west of the No. 3 Orebody, thin lenses of low-grade ore were intersected in brecciated schist, chert and chloritised pegmatite at the contact between the Upper and Lower Mine Sequences. Drilling at Anomaly 4 during the late 1980s failed to intersect significant amounts of high-grade mineralisation.

Jabiluka deposits

A detailed ground radiometric survey over the Jabiluka area was carried out by A.C.A. Howe Australia Pty Ltd on behalf of Pancontinental Mining Ltd in 1971 (Rowntree & Mosher, 1975). The small Jabiluka 1 deposit was detected as a weak ground radiometric anomaly; it had not been recognised in the earlier airborne radiometric surveys. The very large Jabiluka 2 deposit was found in 1973 by drilling along strike to the east of Jabiluka 1, through the overlying barren Kombolgie sandstone (Figs 13 and 14).

Jabiluka 1 and 2 deposits are in the lower member of the Cahill Formation, at the north-eastern margin of the Nanambu Complex. Jabiluka 1 lies just west of a large outlier of the Kombolgie Subgroup but Jabiluka 2 (300 m east of Jabiluka 1) is concealed by up to 200 m of Kombolgie sandstone. A third deposit, Jabiluka 3, was indicated in one drill hole south of Jabiluka 1 (Hegge & others, 1980; B. Tulloch, ERA Ltd mine geologist, personal communication 1994). The intersection is down-dip from Jabiluka 1. Both Jabiluka 1 and 2 deposits occur within an open asymmetric flexure, striking east-south-east and dipping to the south (Fig. 15).

The Jabiluka 1 deposit measures about 400 m in a north-westerly direction and 200 m in a north-easterly direction (Hegge, 1977). It dips south at 15–30º, and in the Main Mine Series the ore zone is up to 35 m thick. Jabiluka 2 deposit extends for at least 1000 m in a west-north-west direction and at least 400 m north–south. It dips south in a series of flexures at between 30º and 60º. The deposit is still open to the south and east at depth (Fig. 15). In the Main Mine Series the ore zones are up to 135 m thick. The deposits are contained in four separate horizons in the lower member of the Cahill Formation: the Upper Graphite Series, Main Mine Series, Lower Mine Series 1 and Lower Mine Series 2. Sixty-seven percent of the uranium mineralisation is in the Main Mine Series.

The metasedimentary sequence at Jabiluka consists of alternating quartz–muscovite–chlorite schist, quartz–chlorite schist, quartz–graphite schist and magnesite–dolomite. Some units are feldspathic, locally containing garnet, sillimanite and zircon.

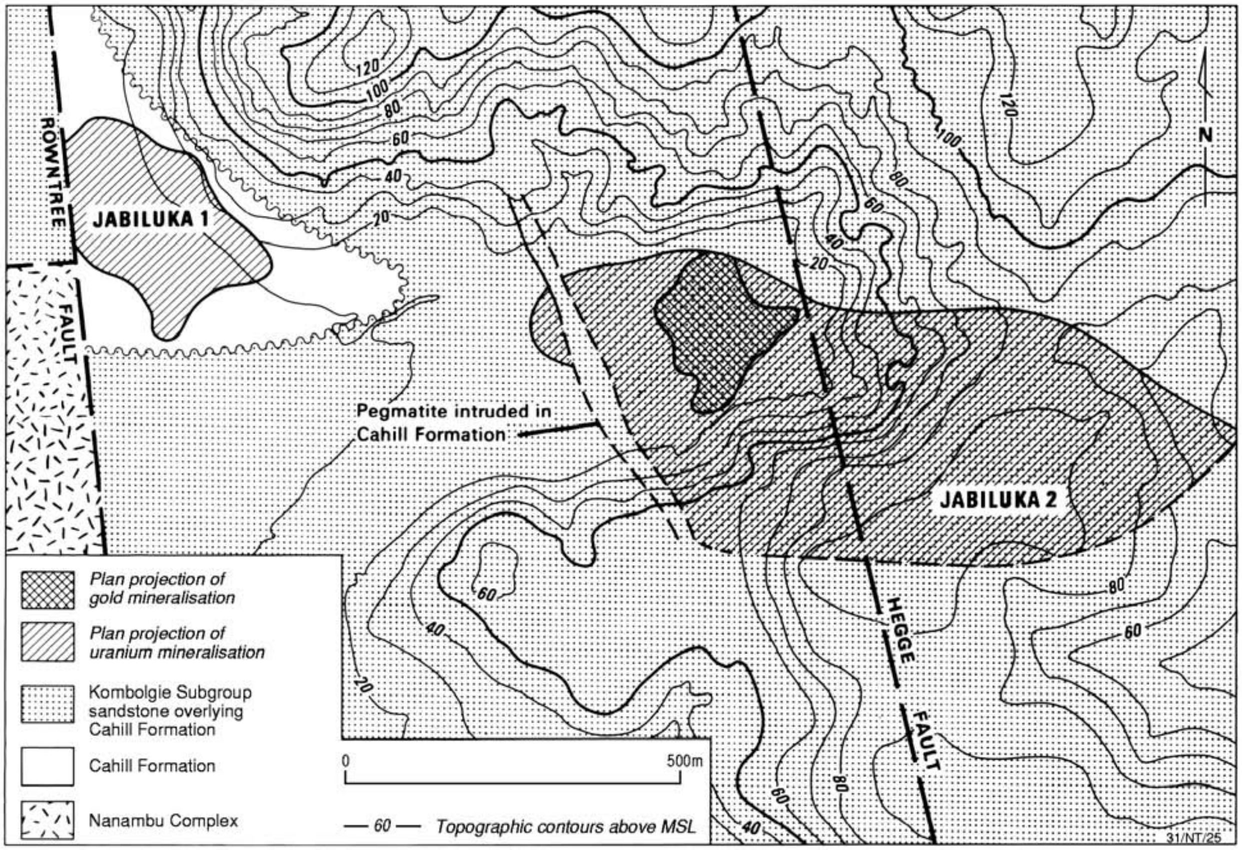

Figure 13. Geological plan of Jabiluka 1 and 2 deposits (after Needham, 1982a, adapted from revised unpublished data by Pancontinental Mining Ltd)

Hancock and others (1990) consider that the sequence is overturned and the orebodies occur along the lower limb of a recumbent fold. In the vicinity of the deposits, retrograde metamorphism has resulted in chloritisation of biotite and garnet, together with sericitisation of feldspar, sillimanite and cordierite.

Primary mineralisation is uraninite with minor coffinite, brannerite and organo–uranium minerals (Binns & others, 1980). Mineralisation is in three main forms: breccias; veins adjacent to breccias; and as disseminations within the schists. The bulk of the economic mineralisation occurs in breccia zones (Hancock & others, 1990).

Wilde (1988) showed that chloritic alteration associated with mineralisation is extensive parallel to the unconformity but appears to decrease with vertical depth below the unconformity. In places, the basal sandstone above the unconformity has been intensely replaced by chlorite. The deposit extends for more than 500 m below the unconformity and remains open at depth (Fig. 15).

Sulphides include pyrite with lesser chalcopyrite and galena. Major gangue minerals are chlorite, quartz, sericite and graphite.

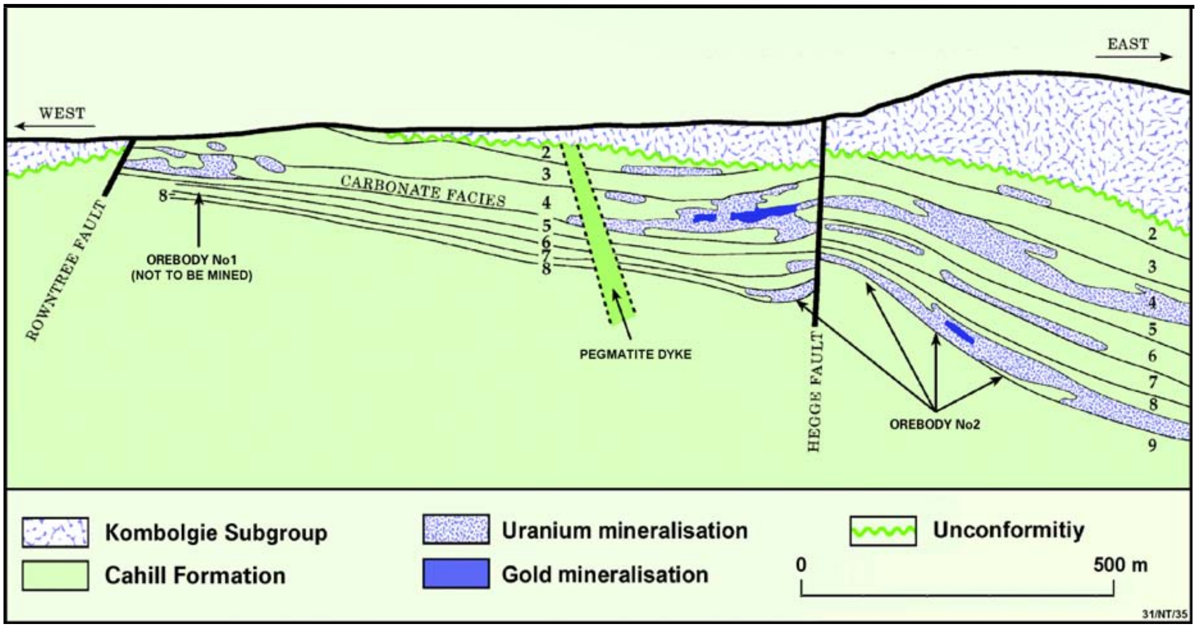

Figure 14. Generalised long-section of Jabiluka 1 and 2 deposits (Kinhill, 1996)

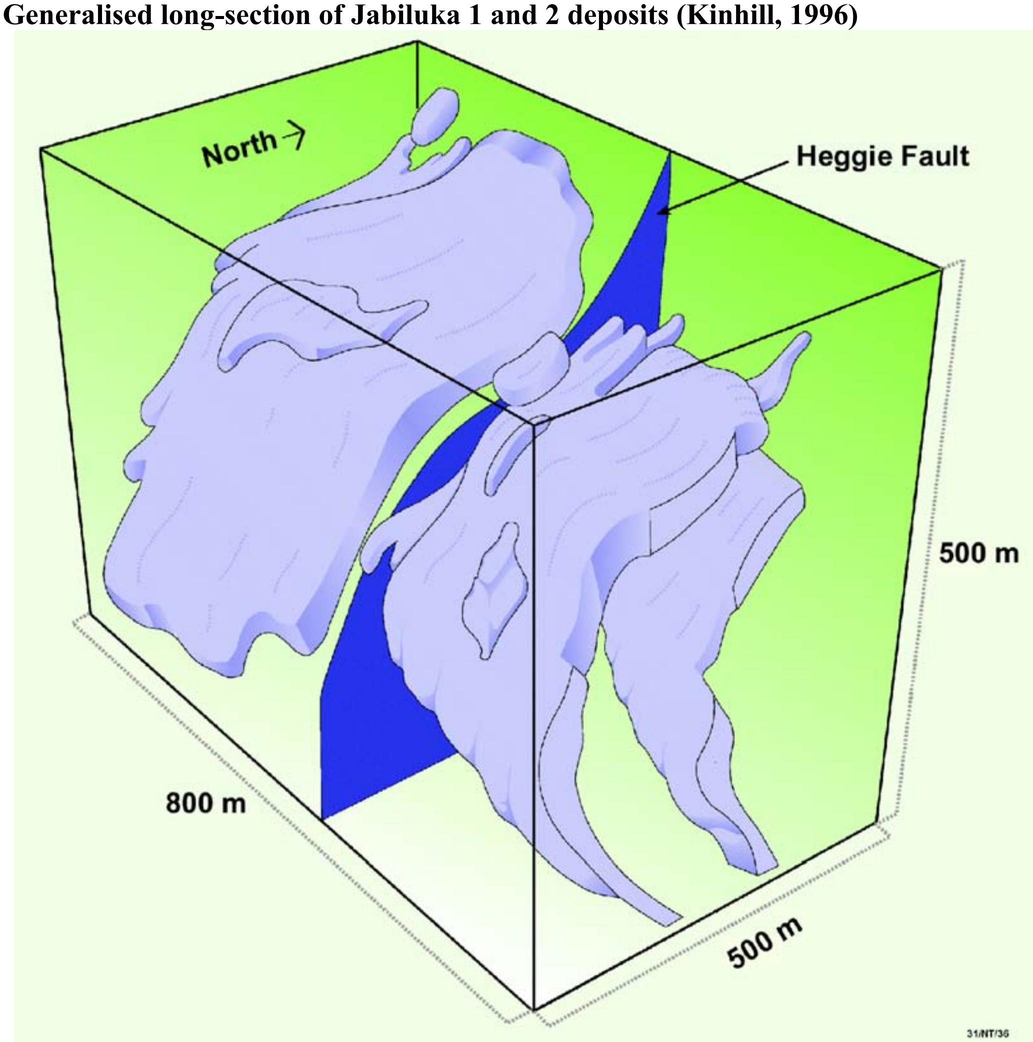

Figure 15. Jabiluka 2 deposit, schematic perspective (Kinhill, 1996)

Resources

The total uranium resources for Jabiluka No. 1 Orebody at a cut-off grade of 0.05% U_3O_8 are 1.3 Mt averaging 0.25% U_3O_8, which represents 3400 t U_3O_8 (Pancontinental Mining Ltd, 1979).

The ore reserve estimates prior to 1998 for Jabiluka No. 2 were based entirely on surface drill hole data. Exposures of the mineralisation in recent underground development, together with results from recent underground drilling, have shown that while the mineralisation is stratabound, the higher-grade ore is mainly in structural zones (breccias). Further drilling of the No. 2 Orebody was carried out from underground during 1999 and the resources were recalculated. The latest ore reserve estimates using this geological information (Table 10) have resulted in higher average grades and lower resource tonnages when compared to previous estimates using the same cut-off grade. Ore resource estimates at a cut-off grade of 0.05% U_3O_8 using the recent geological information are not available.

Table 10. Ore reserves and mineral resources for Jabiluka 2 Orebody as at June 2000, calculated at a cut-off grade of 0.2% U_3O_8 (ERA Ltd, 2000)

Jabiluka 2 Orebody	Mt	Grade % U_3O_8	U_3O_8 (t)
Proved plus probable ore reserves	13.8	0.51	71 000
Measured plus indicated mineral resources*	15.5	0.57	88 000
Inferred resources	15.7	0.48	75 000
Total resources	31.1	0.53	163 000

* Mineral resources are inclusive of those resources modified to produce ore reserves

Gold mineralisation occurs in graphite horizons in the western part of the Jabiluka No. 2 Orebody (Fig. 14). The gold is mainly in breccia zones of the Main Mine Series and the ore averages a thickness of 2 m (Hegge, 1977). The gold zone contains 2.392 Mt ore averaging 3.7 g/t Au and 0.47% U_3O_8 (ERA Ltd, 1992).

Koongarra deposits

The No. 1 Orebody at Koongarra (Figs 16 and 17) was detected in 1969 during an airborne radiometric survey flown on behalf of Noranda Australia Ltd. The anomaly outlined by the airborne survey was small, but follow-up ground surveys delineated a much stronger radiometric anomaly over the deposit in 1970. The No. 1 Orebody and another deeper orebody (No. 2 Orebody) were delineated by drilling, between 1970 and 1973.

In 1979, Noranda Australia Ltd submitted a final Environmental Impact Statement for development and mining of the No. 1 Orebody by open cut (Noranda Australia Ltd, 1978, 1979). In 1980, Denison Australia Pty Ltd purchased the deposit from Noranda. In 1983, the newly elected Commonwealth Labor Government's formulation of the 'Three mines' policy, restricting uranium mining to the Ranger, Nabarlek and Olympic Dam deposits, halted progress towards the development of the Koongarra deposit. Later, Cogema Australia Pty Ltd acquired full ownership of the project in two stages in 1993 and 1995.

Uranium occurs mainly in quartz–chlorite schist and graphitic schist of the lower Cahill Formation, on the hanging-wall side of a north-east trending reverse faulted contact with the Kombolgie Subgroup (Foy & Pederson, 1975). Vertical displacement is probably about 600 m, and strong shearing persists well into the hanging-wall quartz–chlorite schist.

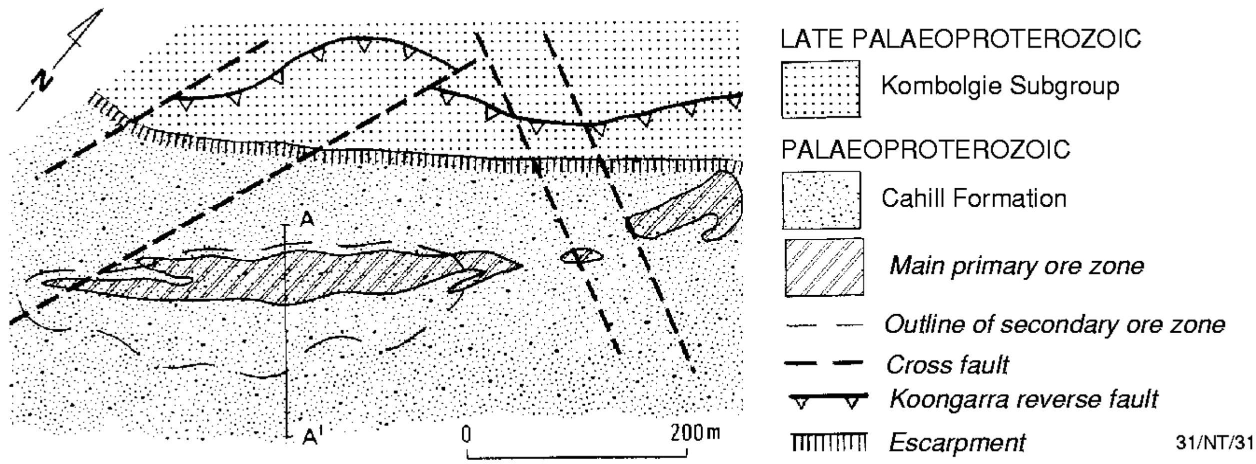

Figure 16. Plan of Koongarra orebodies (from Needham, 1982a, after Foy & Pedersen, 1975, and Hegge & others, 1980)

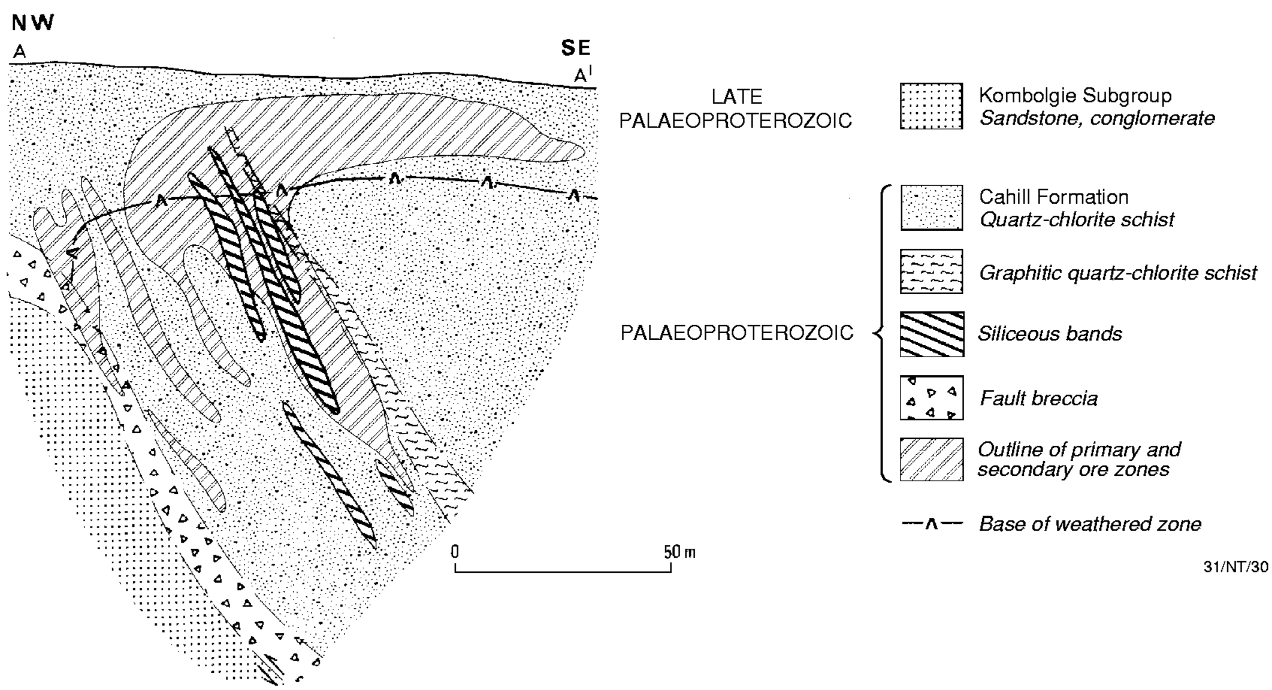

Figure 17. Cross-section, Koongarra No. 1 Orebody (from Needham, 1982a, after Foy & Pedersen, 1975, and Hegge & others, 1980)

Uranium mineralisation occurs in two bodies separated in plan by 100 m. The No. 1 Orebody has a strike length of about 450 m and extends to a depth of 100 m. The primary mineralisation is a series of lenses in a 50 m-wide zone dipping at 55° to the south-east. The secondary mineralisation, in weathered schist above the No. 1 Orebody, comprises ore-grade material dispersed 80 m downslope to the south-east. The No. 2 Orebody is north-east of No. 1 Orebody and has a strike length of 100 m. Mineralisation occurs between 50 m and 250 m below surface and does not extend into the weathered zone (Hegge & others, 1980; Snelling, 1980).

The Palaeoproterozoic sequence at the No. 1 Orebody is upfaulted against the Kombolgie Subgroup, with the development of hematitic quartzite breccia and strongly brecciated and often siliceous quartz–chlorite schist. Quartz–chlorite schist in the hanging-wall up to 50 m above the fault zone is host to the richest uranium ore. The host rocks are physically overlain by a metasedimentary sequence of graphitic quartz–chlorite schist, quartz–chlorite schist, and quartz–mica schist.

Secondary uranium minerals occur to a depth of 25 m and include sklodowskite, kasolite, renardite, metatorbernite, saleeite and curite. The primary ore is uraninite, both crystalline and in sooty amorphous masses. Gold mineralisation is disseminated within the high-grade ore and the wall rocks immediately adjacent to the ore. Pyrite and traces of chalcopyrite and galena are often present in the high-grade ore. The main gangue is quartz, chlorite and mica. A detailed description of the ore mineralogy is given by Snelling (1980, 1990).

Two well defined alteration zones surround the mineralisation (Snelling, 1990):

- an outer zone in which metamorphic biotite and hornblende are replaced by chlorite, feldspar is replaced by sericite, and silicification occurs along fault zones;
- an inner zone which shows intense replacement of the metamorphic mineral assemblage by chlorite, and removal of quartz.

The mineralisation at Koongarra post-dates both the Kombolgie Subgroup and the reverse faulting because it occupies the breccia zones formed by the post-Kombolgie reverse fault. Kombolgie deposition occurred between 1822 Ma and 1720 Ma (Sweet & others, 1999). The Sm–Nd isotopic data on uraninites from Koongarra are strongly scattered but the geological setting and Nd model ages for the least disturbed samples suggest an age of 1600–1650 Ma (Maas, 1989).

Resources

Reserves for the Koongarra No. 1 Orebody were estimated to be 14 500 t U_3O_8 with an average grade of 0.8% U_3O_8. Koongarra No. 2 Orebody has resources of 2000 t U_3O_8 with an average grade of 0.3% U_3O_8 (Cogema, 1996). There is a zone of gold mineralisation occurring both within and adjacent to the uranium mineralisation and this was estimated to contain 3110 kg Au (100 000 oz) with an average grade of 3 g/t Au.

Nabarlek deposit (mined out)

Queensland Mines Ltd discovered the Nabarlek deposit in 1970 during costeaning of a significant airborne radiometric anomaly that had been identified by a gamma-ray spectrometer survey flown over the area during April–June 1970 (Tipper & Lawrence, 1972). During 1970 and 1971, the orebody was delineated by drilling. The deposit was mined and stockpiled between June and October 1979. Mining and processing of the Nabarlek ore is described in an earlier chapter, 'Development and Production'.

Rock types which host the orebody are chlorite schist, biotite–muscovite–quartz feldspar schist and amphibolite of the Myra Falls Metamorphics (Wilde & Noakes, 1990), which are thought to correlate in part with the Cahill Formation (Needham, 1982b,c). The Palaeoproterozoic sequence was metamorphosed to amphibolite grade. The metamorphic rocks are faulted against the Palaeoproterozoic Nabarlek Granite, which has been intersected by drilling at 450 m below the deposit (Wilde & Noakes, 1990). The metamorphic sequence was intruded by a thick (220–250 m) discordant sheet of Oenpelli Dolerite (Fig. 18).

Sandstone outliers of the Kombolgie Supergroup crop out to the immediate north, west and south of the deposit, and by extrapolation the deposit was originally within 50 m of the unconformity prior to erosion of the sandstone cover (Wilde & Noakes, 1990).

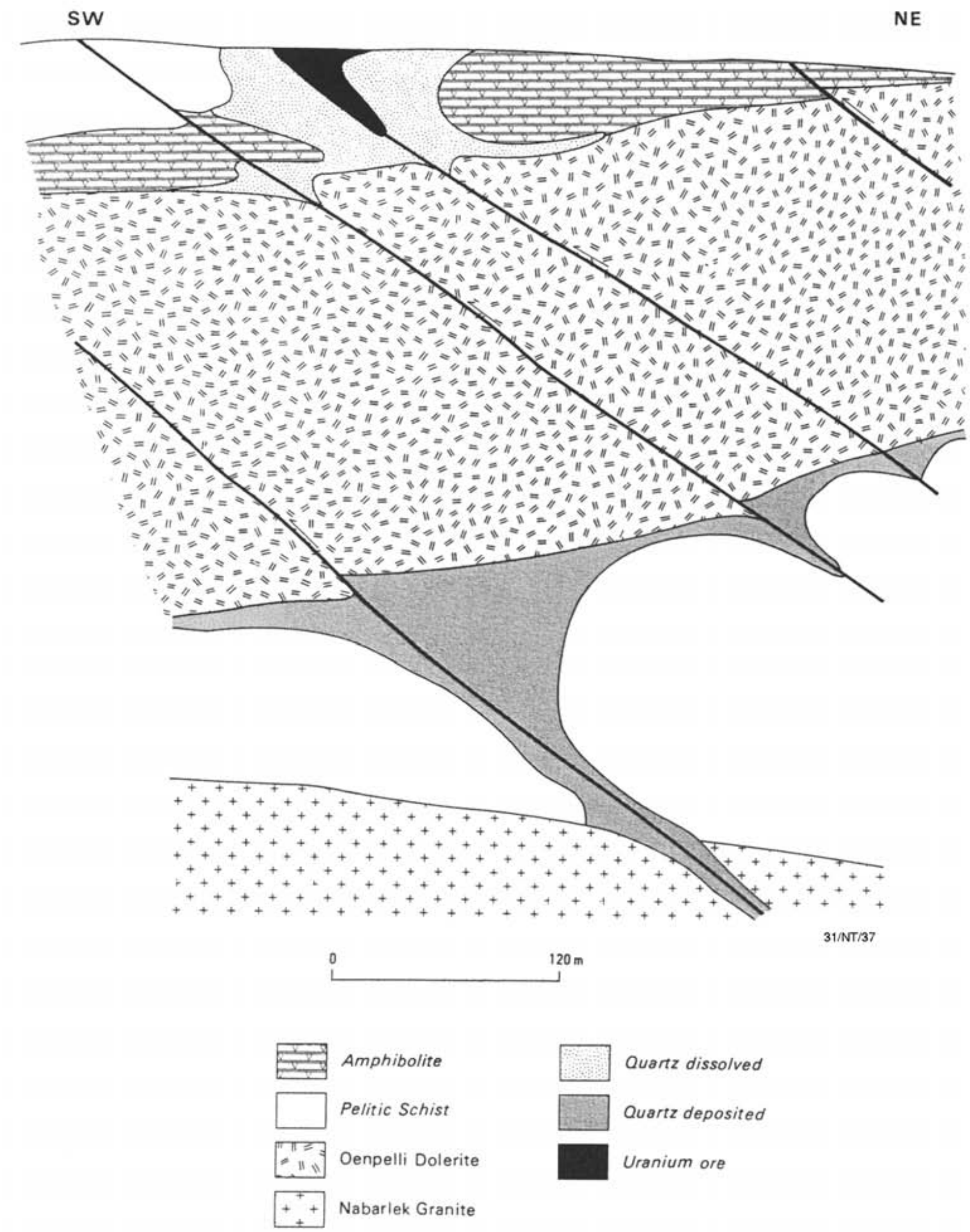

Figure 18. Geological cross-section 9700 m N through the Nabarlek deposit (from Wilde & Noakes, 1990)

The orebody was deposited within the Nabarlek fault breccia and consisted of a high grade core (>1% U_3O_8) in the breccia, and an envelope of low grade disseminated ore (0.1%) (Wilde & Noakes, 1990). The orebody was 250 m long and thinly wedge-shaped in cross-section with an average width of 7 m (Fig. 18). Most of the ore was at a depth of less than 45 m, but the orebody tapered to a maximum depth of 85 m where it was terminated by a sill of Oenpelli Dolerite. Mineralisation was in massive fine-grained dark-green chlorite–sericite–hematite rock, breccia and altered schist (Anthony, 1975; Ewers, Ferguson & Donnelly, 1983). In the primary ore zone, the orebody contained irregular lenses of pure pitchblende (Anthony, 1975). Ewers and others (1983) stated that the primary ore mineral assemblage was dominated by uraninite with minor coffinite and possibly some brannerite. Minor sulphides (less than 0.05%) included galena, chalcopyrite and traces of pyrite.

Two distinct hydrothermal alteration zones are associated with mineralisation (Wilde & Noakes, 1990):

- an outer zone in which metamorphic biotite, feldspar and hornblende are replaced by an assemblage of Fe-rich chlorite, white mica and quartz;
- an inner zone characterised by the presence of pervasive hematite, chlorite, white mica and the removal of quartz.

The Sm–Nd isotopic studies on samples of primary ore have yielded ages of 1616 ± 50 Ma (Maas, 1989). The Sm–Nd data for primary ore samples also reflect an isotopic disturbance at approximately 900 Ma, which is probably the age of post-ore dissolution described by Ewers and others (1983) and Wilde and Wall (1987).

Other deposits and prospects

The **Ranger 68** deposit (Fig. 9), 5 km west of Jabiluka 1, was located by scout drilling along the favourable contact between the Cahill Formation and Nanambu Complex (Hegge & others, 1980). It is completely covered by 30 m of Recent alluvium and Cretaceous sand. The mineralisation is present in chloritised breccia, pegmatoid, and to a lesser extent quartz–sericite–chlorite schist of the lower Cahill Formation, and it occurs adjacent to (<200 m) the contact with the Nanambu Complex (Browne, 1990). The sooty and colloform uraninite mineralisation is immediately below the Cretaceous unconformity. On 2 February 1978, Peko-Wallsend Ltd and Electrolytic Zinc Company of Australasia Ltd announced that the drilling of 10 holes had indicated uranium mineralisation over a distance of 200 m; even now, the boundaries of the mineralised zone have not been defined. Good intersections included 6.75 m at 0.536% U_3O_8 (hole S1), 7.45 m at 0.538% U_3O_8 (hole S2), and 8.00 m at 0.789% U_3O_8 plus 28.00 m at 0.392% U_3O_8 (hole S4).

Resources within the mineralised zone were estimated to be 1.5 Mt ore averaging 0.357% U_3O_8, using a cut-off grade of 0.1% U_3O_8, i.e. more than 5000 t U_3O_8 (Browne, 1990). Copper mineralisation occurs as sooty chalcocite within the uranium deposit. The best intersection was 5.75 m at 1.1% Cu. No further exploration was carried out after 1977, and in 1979 the Kakadu National Park that covers this area was proclaimed.

Ranger 4 is 5 km west-south-west of Ranger 68. Drilling has indicated a small body of medium-to-low-grade uranium mineralisation in the lower Cahill Formation.

The **Hades Flat** prospect is 10 km north of the Ranger 1 deposits. Again, the mineralisation is in the lower Cahill Formation, here faulted against the Nanambu Complex (Hegge & others, 1980). Pitchblende occurs in fractures and breccia zones close to the fault and also in chlorite schist further away from the Nanambu Complex. The joint venturers of the Jabiluka project stated in their draft Environmental Impact Statement (Pancontinental Mining Ltd, 1977) that the Hades Flat prospect contains at least 726 t U_3O_8; however, it has not been fully delineated.

At the **7J** prospect, 3 km north-east of Hades Flat, uranium and gold mineralisation were intersected in chlorite schists below the Kombolgie sandstone. The Jabiluka joint venturers stated that further drilling at 7J is likely to confirm the existence of a viable orebody (Pancontinental Mining Ltd, 1977). However, no work has been done on it since 1973 because it lies within Stage One of the Kakadu National Park (Hegge & others, 1980).

The **Caramal (Nabarlek 2)** deposit is 21.5 km south-south-east of the Nabarlek deposit and lies within the Arnhem Land Aboriginal Reserve. Secondary uranium minerals are exposed in schist at the surface and primary mineralisation was intersected by diamond drilling in schist and carbonate rock under the

Kombolgie Subgroup sandstone. Drilling at Caramal during 1970–75 outlined ‘resources of 2500 t U_3O_8’ (Pioneer Concrete, 1988). These resources have not been completely tested.

The **Austatom** prospect is 28 km west of the Ranger 1 deposits (Fig. 9). The uranium mineralisation is in weathered Cahill Formation schist and is almost totally concealed by barren (?)Cretaceous sand. The small portion of the mineralised zone exposed at the surface was located during a ground radiometric survey and geological mapping in 1976. The best auger hole intersections, as stated by the Australian Atomic Energy Commission in a press release (December 1976) were 0.48% U_3O_8 over 1.5 m, and 0.21% U_3O_8 over 13 m. Anomalous amounts of copper, lead, zinc, cobalt, nickel and manganese are also associated with the uranium mineralisation. Secondary uranium occurs in north-north-westerly trending weathered and partly brecciated schist adjacent to a dolomite sequence to the east. Both lithologies are part of the lower Cahill Formation and the prospect is 700–800 m west of the Nanambu Complex. The Austatom prospect is within 25 km of the flat-lying sandstone outcrop of the late Palaeoproterozoic Kombolgie Subgroup that overlies the Palaeoproterozoic Cahill Formation. It is probable that the unconformity between the sandstones and the Cahill Formation was close to the present surface at the Austatom prospect prior to erosion and escarpment retreat.

The **Black Rock** prospect within the Arnhem Land Aboriginal Reserve, 55 km north-north-west of Nabarlek, was discovered in the early 1970s by Union Carbide Exploration Corporation during exploration over a large Authority to Prospect, which extended from latitude 12°15′S northwards to the Arnhem Land coastline. At Black Rock, mineralisation was found at two sites, referred to as the Schist and Laterite anomalies, which are 1 km apart. At the Schist anomaly, mineralisation occurs in granitic gneisses (Nimbuwah Complex) adjacent to the unconformity with the Kombolgie sandstone. The geological setting is similar to that at Nabarlek. A total of 79 auger holes and 12 diamond holes were drilled to test the anomaly. Mineralisation was intersected in several holes, the best intersection being 6.1 m of 0.21% U_3O_8. The Laterite anomaly is essentially laterite with outcrops of amphibole chlorite gneiss. It was tested by a total of 257 auger holes, most of which were only drilled to shallow depths. Uranium mineralisation was intersected in a number of holes, the best intersections were 1.4 m of 0.79% U_3O_8, and 0.6 m of 0.32% U_3O_8. The mineralisation has not been tested at depth below the weathered zone.

Other uranium prospects have been discovered within the Arnhem Land Aboriginal Reserve, 36 km south-south-west of Nabarlek at **Beatrice** (Fig. 9), 15 km south-west of Nabarlek at **Gurrigarri** and **Garrunghar**, 8.5 km south-west of Nabarlek at **Mordijimuk**, 35 km north of Jabiluka at **Arrara** (Hegge & others, 1980) and 25 km north-west of Nabarlek at **Tadpole** (Needham, 1988b).

RUM JUNGLE URANIUM FIELD

The Rum Jungle uranium field (Fig. 19), 90 km south of Darwin, was the first to be discovered in the Pine Creek uranium province. The initial discovery was made by Mr J.M. White in 1949 who reported that some minerals in outcrops north-east of Rum Jungle railway siding resembled uranium minerals illustrated in the booklet, *Radioactive Mineral Deposits* (BMR, 1948). The presence of secondary uranium minerals was confirmed by BMR staff and BMR then began a systematic uranium exploration program to assess the prospect and the surrounding area. By the end of 1951, White’s discovery was proved to be a significant uranium deposit and BMR had also located a uranium deposit at Dyson’s.

Following the verification of an economic orebody at White’s, discussions were held between the Commonwealth, United Kingdom and United States Governments in 1952 which led to the provision of funds by the UK–USA Combined Development Agency for the exploitation of the Rum Jungle deposits (Warner, 1976).

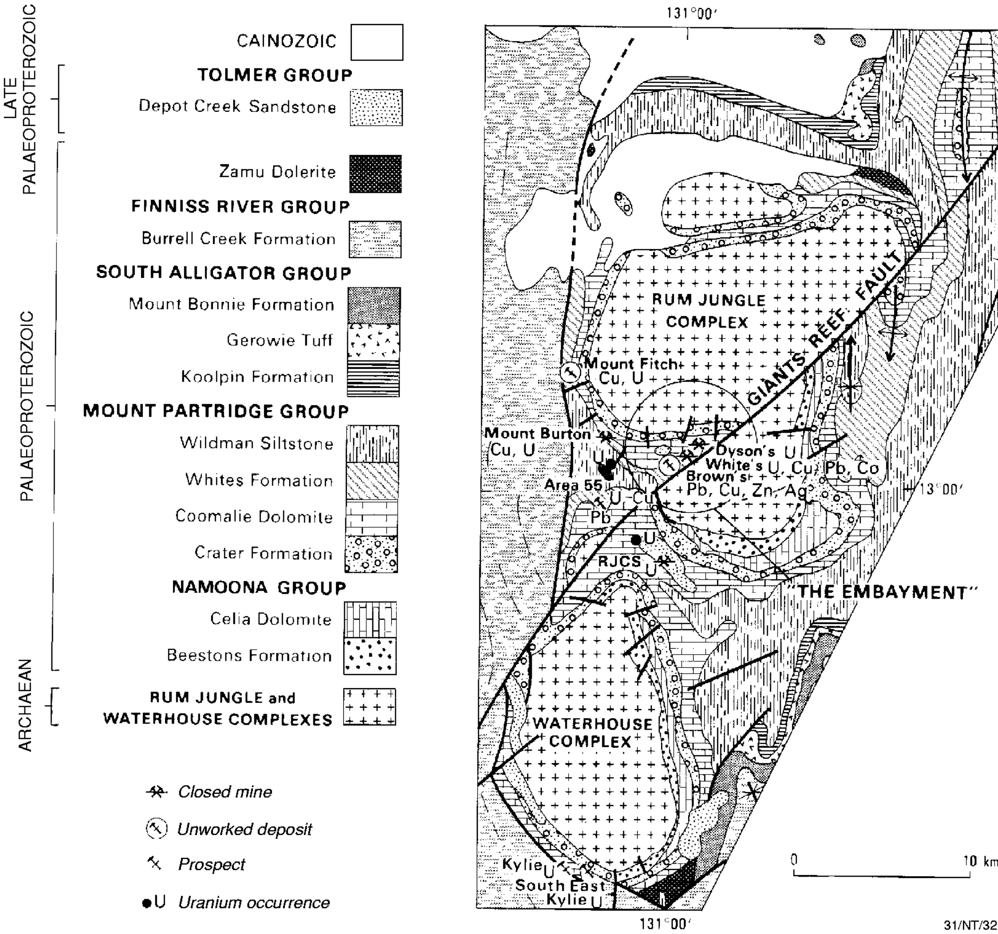

Figure 19. Geology of the Rum Jungle uranium field (modified after Ewers & others, 1984)

In 1953, Territory Enterprises Pty Ltd (TEP), a subsidiary of Consolidated Zinc Pty Ltd (CZP), was formed to establish and manage a mining operation at White's uranium deposit on behalf of the Commonwealth Government. In the same year, the *Atomic Energy Act (1953)* was passed and the Australian Atomic Energy Commission (AAEC) was established. The Hundred of Goyder, a land subdivision of about 435 km^2, which enclosed the Rum Jungle uranium deposits, was declared a prohibited area. A uranium ore treatment plant was built on a site between White's and Dyson's, and operations commenced in September 1954. The plant was designed to produce about 180 t U_3O_8/year from ores grading 0.23–0.35% U_3O_8 (Barlow, 1962; Warner, 1976). A total of 3530 t U_3O_8 was recovered at the Rum Jungle treatment plant during 1954–71, from four deposits in the Rum Jungle field and from 10 000 t of custom-treated ore from elsewhere.

The AAEC continued to finance uranium exploration in the area, carried out by both BMR and TEP, until 1971. Another three uranium deposits — Mount Burton, Rum Jungle Creek South and Mount Fitch — and numerous radioactive prospects were outlined by 1968. The Australian Mining and Smelting Company Ltd (AM&S), a subsidiary of CZP (later Conzinc Riotinto of Australia Ltd (CRA)), also had an arrangement to explore certain base metal deposits. AM&S drilled the base metal deposits at Brown's and Area 55, and also mined and treated copper ore from the Intermediate mine. Uranium mining in the field ended at Rum Jungle Creek South in 1963, but treatment of stockpiled ore continued until 1971.

Between 1971 and 1983 exploration was continued in the area by exploration companies, and Uranerz Australia Pty Ltd discovered the Kylie and South East Kylie prospects (Pagel, Borshoff, & Coles, 1984).

Regional geological setting

The Rum Jungle uranium field is on the western side of the Pine Creek Inlier (Figs 9 and 10) where Palaeoproterozoic metasediments are unconformably draped around two Archaean granitic basement complexes (Fig. 19) — the Rum Jungle Complex to the north and the Waterhouse Complex to the south (Fraser, 1980; Crick, 1987). Uranium and base metal mineralisation occur in graphitic or chloritic pyritic phyllite of the Whites Formation at its contact with the underlying dolomite–magnesite of the Coomalie Dolomite. The Palaeoproterozoic sequence is locally unconformably overlain by hematite quartzite breccia (Buckshee Breccia — a regolith?) and by late Palaeoproterozoic sandstone and conglomerate. The larger deposits (White's, Dyson's, Rum Jungle Creek South) and many of the smaller prospects show a spatial association with this unconformity.

The Palaeoproterozoic sequence has been metamorphosed to low-grade greenschist facies. The two basement complexes together with the Proterozoic rocks are displaced dextrally 4–5 km along the regional Giant's Reef Fault. The displacement has created a wedge-shaped embayment of sedimentary rocks, thrown against the Rum Jungle Complex in the south-eastern block.

A broad mineral zoning trend has been noted by Miezitis (1969) and Fraser (1975, 1980). Four of the uranium and base metal deposits are in the Embayment: Dyson's (uranium) in the north-east, followed to the south-west by White's (uranium, copper, lead, cobalt, nickel), Intermediate (copper, uranium; immediately south-west of White's) and Brown's (lead, zinc, copper, cobalt, nickel; 1 km south-west of Intermediate). The Mount Burton (uranium, copper) and Mount Fitch (uranium, copper) deposits are peripheral to the Rum Jungle Complex 5 km west and 7 km north-west of White's. Rum Jungle Creek South (uranium; 'RJCS' in Fig. 19) is 5 km south-west of White's.

Roberts (1960) carried out mineragraphic studies on ore samples from White's deposit and concluded that uraninite and pyrite mineralisation preceded a period of shearing, which was followed by the introduction of copper, cobalt and lead sulphides. Richards (1963) obtained a $^{207}Pb/^{206}Pb$ age of 1015 Ma on a uraninite sample from White's deposit; however, he concluded from Roberts's work that the uraninite was probably older than 1015 Ma because it was invariably altered. Isotopic dating of mineralisation at the Kylie prospect yielded ages of 1627 ± 45 Ma (Ahmad & others, 1993).

Deposits

Four deposits were mined in the Rum Jungle uranium field — Dyson's, White's, Mount Burton and Rum Jungle Creek South — two of which also produced copper. The amounts of uranium ore mined from the various open cuts, as given in Table 11, are derived from Berkman (1968). Copper was mined from the Intermediate open cut.

The 403 000 t mined from White's (Table 11) includes 87 000 t of low-grade uranium–copper ore that was treated at the plant, according to Berkman (1968), whereas Warner (1976) excluded this material. Regardless of whether or not this material was treated, the total production of U_3O_8 from the plant amounts to 3530 t. There appears to be no adequate record of the quantity of uranium recovered at the plant from the individual pits.

Dyson's orebody was found by trenching a ground radiometric anomaly in 1950. The deposit was 60 m long, 8 m wide and 100 m deep. Initially (1953–54), TEP mined the deposit by both underground and open cut methods, with further open cut mining in 1954–57, to a maximum depth of 65 m. The mineralisation was hosted in strongly sheared graphitic slate of the Whites Formation near its contact with the Coomalie Dolomite. The secondary uranium minerals were saleeite and lesser autunite and sklodowskite. Below 25 m, pitchblende was present as veins and disseminations. Drilling by TEP in 1968–69 showed that uranium mineralisation persisted as narrow zones to depths in excess of 100 m.

Table 11. Uranium and copper ore treated from the Rum Jungle uranium field*

Mine	Ore (t)	Grade
Dyson's	157 000	0.34% U_3O_8
White's	403 000	0.27% U_3O_8, 2.7% Cu
	295 000	2.8% Cu, 0.3% Co
Mount Burton	6 000	0.21% U_3O_8, 1.04% Cu
Rum Jungle Creek South	665 000	0.43% U_3O_8

*Copper ore was also mined from the Intermediate open cut.

White's deposit is approximately 1 km south-west of Dyson's. Like Dyson's, White's was first (1953) mined underground but during 1954–58 the deposit was mined by open cut methods to a depth of 112 m. The orebody was about 150 m long and some of the mineralisation persists to depths beyond 300 m. Uranium and base metal mineralisation was within graphitic, sericitic, chloritic and pyritic phyllites of the Whites Formation close to its contact with the underlying Coomalie Dolomite. The ore minerals formed four conformable layers and the zoning from the top downwards towards the Coomalie Dolomite contact, as described by Spratt (1965) and Fraser (1980), was as follows:

(i) (top) cobalt–lead zone: up to 5 m (galena, lesser sphalerite and carrollite);
(ii) cobalt–nickel zone: up to 3 m (linnaeite, carrollite, bravoite, gersdorffite);
(iii) copper–cobalt zone: up to 3 m (bornite, chalcocite, linnaeite, carrollite);
(iv) (base) uranium–copper zone: up to 18 m wide (pitchblende and chalcopyrite; minor galena, aikinite, native bismuth, gersdorffite).

Only the uranium–copper zone cropped out at the surface, as a narrow gossan containing torbernite, autunite with lesser phosphuranylite, gummite, saleeite and johannite.

The results of detailed investigations of **White's East** prospect, done with the knowledge gained after the discovery of the Alligator Rivers deposits, were published by Paterson, von Pechmann and Borshoff (1984). This prospect lies between White's and Dyson's and was investigated from 1980 to 1982 by Uranerz Australia Pty Ltd and AOG Minerals Ltd. Paterson and others (1984) concluded that the uranium mineralisation at White's East is of the unconformity-related type and is very similar to the deposits in the Alligator Rivers uranium field. Uranium ore zones are hosted within the Palaeoproterozoic Whites Formation near its unconformable contact with the late Palaeoproterozoic sandstone and breccia–conglomerate of the Depot Creek Sandstone. The primary ore assemblage is dominated by pitchblende, which together with chlorite and/or sericite and hematite occupies kinked and brecciated zones associated with reverse faulting. Chlorite is the most widespread alteration mineral associated with the uranium mineralisation at White's East, and magnesian alteration is prominent adjacent to, and along, structures controlling uranium deposition. A multiphase hydrothermal mineralising process was proposed for the origin of the uranium mineralisation, and two generations of uranium mineralisation have been identified (Paterson & others, 1984).

South-east of White's mine, copper was the dominant metal at the Intermediate mine, while lead, zinc, copper, cobalt and nickel occur in Brown's deposit at the south-western end of the Embayment.

South of the Embayment, on the southern side of the Giant's Reef Fault, was the largest of the uranium deposits, **Rum Jungle Creek South**. The deposit was found by TEP grid drilling during follow-up work on some weak airborne radiometric anomalies (Berkman, 1968; Fraser, 1980). Detailed diamond-drilling and a prospecting shaft were used to locate a uranium deposit 245 m long and 60 m wide within a much broader zone of apparently random uranium mineralisation. As in the Embayment, the orebody was in the Whites Formation close to the underlying Coomalie Dolomite (Ahmad & others, 1993). Ore-grade mineralisation was confined to pyritic and chloritic phyllites, with some uranium in the underlying graphitic phyllite, in a synclinal structure. The sole ore mineral was pitchblende, as a fine sooty coating on cleavage planes and joints. The deposit was mined by open cut from 1961 to 1963 to a maximum depth of 68 m.

At the small **Mount Burton** open cut, systematic trenching of the Whites Formation/Coomalie Dolomite contact by TEP in 1954 revealed near-surface secondary uranium mineralisation. Berkman (1968) stated that the deposit was confined to the crest of an anticlinal fold as depicted by the dolomite–slate contact. The ore was mined by open cut during October–November 1958. The oxidised zone contained torbernite, malachite and minor chalcocite and native copper. Pitchblende, pyrite and chalcopyrite extended below the weathered zone.

The **Mount Fitch** prospect was first detected as a radiometric anomaly from airborne and ground follow-up surveys. A program of pattern diamond drilling by TEP during 1966–70 located a low grade uranium–copper deposit. The uranium is in a shallow syncline at the contact of the Coomalie Dolomite and Whites Formation. Unlike the other uranium deposits the main uranium body is confined to a breccia zone in the magnesite. Berkman and Fraser (1980) estimated that approximately 1500 t U_3O_8 was present. Secondary copper in residual clays was estimated to amount to 290 000 t ore with a possible average grade of 0.6% Cu. Between 1977 and 1983 the prospect was re-evaluated by Uranerz Australia Pty Ltd (UAL), which concluded that uranium mineralisation occurs in sheared and brecciated rocks along steeply dipping fault zones (Pagel & others, 1984). Brecciated chloritised dolomite and dolomite/chlorite/graphite schist are the major host rocks. The mineralised fault zones were found to transect stratigraphic boundaries at high angles and extend beyond the limits of TEP's drilling. However, the tonnage and grades previously established by TEP were only marginally improved by UAL's drilling.

In 1987, UAL found the **Kylie** prospect by using ground radiometric surveys. The prospect is 400 m from the southern margin of the Waterhouse Complex and occurs in a sequence of dolomite/magnesite with lenses of graphite-, chlorite-, tremolite-, tourmaline- and biotite-rich metapelites. This sequence overlies the Crater Formation and belongs to the Coomalie Dolomite. Uranium mineralisation is hosted in steeply dipping metapelite and carbonate next to a downfaulted block of the Palaeoproterozoic Depot Creek Sandstone. Mineralisation is generally confined to zones of brecciation and chloritisation in dolomite/magnesite rock and quartz–chlorite schist. Extensive alteration is shown by complex association of chlorite/magnesite, talc, tourmaline, fluorapatite, rutile, silica and sericite with the mineralisation. Mineralisation also occurs in fault-gouge zones (Pagel & others, 1984).

The **South-east Kylie** prospect is 2 km south-east of Kylie and the main mineralised zone is in sheared metapelite where mineralisation is associated with brecciated quartz–chlorite schist, sheared pyritic carbonaceous schist and minor chloritic carbonaceous dolomite. Copper and lead are also associated with the uranium mineralisation.

Other prospects and occurrences containing uranium mineralisation in the Rum Jungle uranium field are **Mount Fitch North**, 1.5 km north of Mount Fitch; **Dolerite Ridge**, 2 km south-east of Mount Burton; and **Rum Jungle Creek** and **Area 55**, 1 km and 4.5 km north-west of the Rum Jungle Creek South open cut. The **Woodcutters** uranium occurrences are east of the Rum Jungle Complex. **Brodribb** and **Ella Creek** are in the Koolpin Formation on the northern margin of the Rum Jungle Complex, about 20 km north-north-east and north-east respectively of White's (Crick, 1987). The **Waterhouse** prospects are south of the Rum Jungle Complex and east of the Waterhouse Complex. **Spring Creek** and **Riverside** prospects are along the southern margin of the Waterhouse Complex (Ahmad & others, 1993).

SOUTH ALLIGATOR VALLEY URANIUM FIELD

The smallest uranium field in the Pine Creek uranium province is in the South Alligator River valley, 220 km south-east of Darwin (Figs 9 and 20). Coronation Hill was discovered by a BMR geologist in June 1953. Intensive prospecting by private companies followed this initial discovery and located another 13 small uranium deposits and some 15 prospects, most of which occur in a north-west-trending structural belt 24 km long and 3 km wide. Between 1956 and 1964 some 874 t of U_3O_8 (Table 12) was mined from the 14 small deposits (Foy, 1975). The uranium was sold under contract to the Combined Development Agency (the joint UK and USA uranium purchasing agency) and the United Kingdom Atomic Energy Authority. During the earlier years, parcels of ore were custom-treated at Rum Jungle. From 1959, the uranium ore was treated at Moline, about 48 km west of the field in a plant converted to solvent extraction technology for recovery of uranium. Some ore was treated at a much smaller plant at the Rockhole mine. A gravity treatment plant was built at El Sherana to produce concentrates of pitchblende and gold. Uranium exploration around the South Alligator Valley continued and intensified in the first half of the 1970s, and although many radioactive prospects and anomalies were found, no major uranium deposit was discovered.

Table 12. Production from the South Alligator Valley uranium mines (after Foy, 1975)*

Mine	U_3O_8 (t)	Grade % U_3O_8
El Sherana	226	0.55
El Sherana West	185	0.82
Rockhole (Rockhole 1, Rockhole 2, O'Dwyers, and Sterrets)	152	1.12
Palette	124	2.45
Saddle Ridge	78	0.24
Coronation Hill	75	0.26
Scinto 5	22	0.37
Scinto 6	3	0.15
Koolpin Creek	3	0.13
Skull	3	0.50
Sleisbeck	3	0.45

*Gold production: El Sherana 0.33 t Au; El Sherana West 0.007 t Au; minor amounts from the Rockhole Group, Palette and Coronation Hill.

The Coronation Hill Joint Venture (CHJV), which comprised BHP Gold Mines Ltd, Pioneer Mineral (Gold) Pty Ltd and Norgold Limited, carried out an exploration program for gold in the South Alligator Valley from 1984 to 1989. Exploration and drilling defined a gold–platinum–palladium orebody at Coronation Hill. Six holes were also drilled to explore for extensions of the uranium–gold mineralisation at El Sherana West.

Stage 3 of the Kakadu National Park together with the Kakadu Conservation Zone, which was entirely within Stage 3, was proclaimed in June 1987. The conservation zone (originally 2252 km^2) enclosed the areas of known mineralisation including the South Alligator Valley uranium field. In October 1989 the conservation zone was reduced to an area of approximately 47 km^2 which covered the South Alligator Valley from 3 km north-west of El Sherana to approximately 2 km south-east of Coronation Hill. The CHJV submitted a proposal to mine the Coronation Hill gold–platinum–palladium deposit. In April 1990, the Commonwealth Government instructed the Resource Assessment Commission (RAC) to carry out an assessment of the economic, environmental and cultural considerations relating to land uses in the new conservation zone, including an assessment of the impact of the proposed mining operations at Coronation Hill. A considerable amount of research work on the mineral resources and mineral potential of the conservation zone was commissioned by the RAC.

From 1987 to 1990, BMR carried out a major investigation of the geology and mineralisation of the South Alligator Valley. This work included four studies: structural mapping and interpretation of the structural controls of mineralisation (Valenta, 1991); a regional stream sediment geochemical survey; geochemical rock chip sampling of the old mines and prospects; and an assessment of the mineral potential of the new conservation zone (Cruikshank, 1990; Miezitis, 1990; Wyborn & others, 1990). Part of this work was funded by the RAC.

The final report of the RAC inquiry was presented to the Government in May 1991. In June 1991 the Government announced that mineral exploration and mining would not be permitted in the conservation zone (Resource Assessment Commission, 1991). The zone was subsequently incorporated into the Kakadu National Park

Regional geological setting

The South Alligator Valley uranium field lies within a north-west-trending zone of folded and faulted Palaeoproterozoic metasediments exposed in the South Alligator Valley (Fig. 20). The regional geology of the South Alligator Valley has been described by Crick and others (1980), Needham and Roarty (1980), Needham and Stuart-Smith (1985), Needham (1987), Needham, Stuart-Smith and Page (1988), Valenta (1990, 1991), Wyborn and others (1990) and Jagodzinski (1999).

The Palaeoproterozoic rocks in the region have been divided into four main sequences with each sequence separated by an unconformity (Needham & others, 1988) (Fig. 20):

Late Palaeoproterozoic	Kombolgie Subgroup
Palaeoproterozoic	Edith River Group
	El Sherana Group
	Pine Creek Inlier sequence

Each sequence shows differing styles of folding, metamorphism and alteration (Wyborn & others, 1990; Valenta, 1991).

In the Pine Creek Inlier sequence, the oldest rocks are carbonaceous shale, siltstone, carbonate and sandstone of the Masson Formation. Next in age (Fig. 20) are the Stag Creek Volcanics, a sequence of altered basalt breccia, basalt flows and dark green tuffaceous shale conformably overlying the Masson Formation. Unconformably overlying these volcanics are coarse feldspathic quartzite and conglomerate of the Mundogie Sandstone. The Koolpin Formation is a sequence of interbedded dolomite, siltstone and carbonaceous shale which rest unconformably on the older metasediments. At the base of the Koolpin is either massive chert-banded ferruginous siltstone with bands of carbonaceous shale or, in some areas, massive dolomite with algal structures.

The Gerowie Tuff (tuffs and argillite) and Shovel Billabong Andesite are interbedded with the upper part of the Koolpin Formation (Fig. 20). The Kapalga Formation is an assemblage of chert-banded ferruginous siltstone and shale, with greywacke. The lower portion of the Kapalga Formation is stratigraphically equivalent to the Koolpin Formation. The Zamu Dolerite forms extensive sills mainly in the Koolpin Formation.

The Pine Creek Inlier sequence was subjected to a major period of deformation and regional metamorphism during the 1880–1850 Ma Barramundi Orogeny. Three phases of deformation can be recognised (Valenta, 1990, 1991; Wyborn & others, 1990). The first phase was isoclinal folding with widespread development of bedding-parallel cleavage. Secondly, the formation of regional-scale north-westerly folds and a penetrative cleavage; thirdly minor north-east folds and associated cleavage.

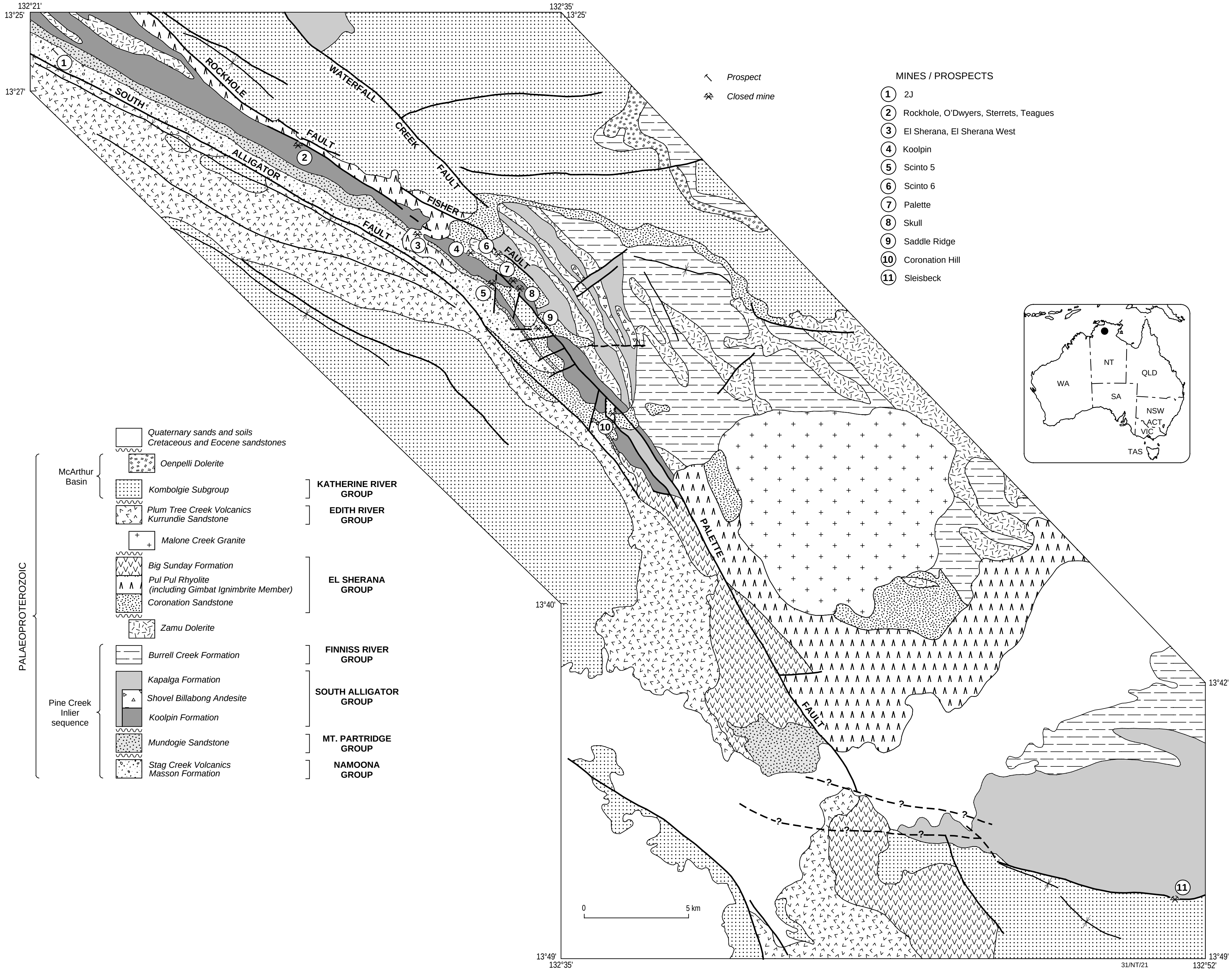

Figure 20. Simplified geology of the South Alligator Valley uranium field (compiled from maps in Needham, 1988a; Friedmann & Grotzinger, 1991; Valenta, 1991; Jagodzinski, 1999)

Following orogenesis, two suites of dominantly felsic volcanics and volcanoclastics (El Sherana and Edith River Groups) accumulated in a graben-like structure which extended over approximately the area of the present South Alligator Valley (Needham, 1987; Needham & others, 1988). The El Sherana Group was deposited at about 1829 Ma (1828.6 ± 5.1 Ma for Pul Pul Rhyolite; Jagodzinski, 1999) and unconformably overlies the geosynclinal sequence. It comprises basal coarse sandstone and felsic volcanics of the Coronation Sandstone; massive rhyolite, ignimbrite, quartz feldspar porphyry and basalt of the Pul Pul Rhyolite; greywacke, shales and tuffs of the Big Sunday Formation. The El Sherana Group rocks were folded, eroded and subjected to further faulting before deposition of the Edith River Group at 1822 ± 6 Ma (Jagodzinski, 1999). This Group includes basal polymictic conglomerate and sandstone of the Kurrundie Sandstone overlain by ignimbrites and minor basalt of the Plum Tree Creek Volcanics (about 1822 Ma). The Palaeoproterozoic rocks were intruded by the Oenpelli Dolerite in late Palaeoproterozoic.

After a period of folding and erosion, thick sandstone sequences of the Kombolgie Subgroup were deposited unconformably over the Palaeoproterozoic rocks some time between 1822 Ma, the age of the Plum Tree Volcanics, and 1720 Ma, the age of the Jimbu Microgranite intruding sediments near the top of the Katherine River Group (Sweet & others, 1999).

The following main geological features controlled the formation of uranium–gold deposits (Needham 1987, 1988a; Wyborn 1990b, 1992; Mernagh & others, 1998):

- the deposits lie close to the unconformity between Coronation Sandstone (sandstone and felsic volcanics) and Koolpin Formation (cherty ferruginous siltstone and carbonaceous siltstone) (Fig. 21),
- the deposits (except Coronation Hill and Sleisbeck) are either completely or mainly hosted by fractured cherty ferruginous siltstone. In some deposits, secondary uranium mineralisation extends into the adjacent sandstone and close to faulted contacts between the Kombolgie Subgroup and the Koolpin.
- the deposits occur along the north-west-trending dextral strike-slip fault system (Valenta, 1990, 1991). Most of the deposits are on or near the Rockhole–El Sherana–Palette fault system.

Displacements along these fault zones formed either approximately horizontal or vertical openings (zones of dilation) at fault bends of intersections. These openings controlled the shape of the ore zones. El Sherana and Saddle Ridge are examples of sub-horizontal ribbon-shaped orebodies, whereas Palette, Skull and Coronation Hill are vertical pipe-like bodies. The main north-west-trending fault system in the South Alligator Valley shows a long movement history, beginning before the deposition of the El Sherana Group and ending after deposition of the Kombolgie sandstone (Valenta, 1991).

All the major uranium deposits are surrounded by alteration zones characterised by the presence of muscovite–chlorite ± kaolinite ± biotite ± hematite (Wyborn, 1992). Hematite is the most extensive alteration mineral.

Hills and Richards (1972) and Cooper (1973) re-interpreted uranium and lead isotope measurements obtained by Greenhalgh and Jeffrey (1959) and found that five pitchblende samples from the El Sherana, Palette and Sleisbeck deposits indicated an age of 815–710 Ma. Another two samples from Palette suggested another mineralisation or secondary solution and redeposition of uranium at 500 Ma.

Needham (1987) proposed that uranium was derived by leaching of the felsic volcanics mainly in the Coronation Sandstone. Uranium was transported by oxygenated groundwaters along interbeds of permeable sandstone in the Coronation Sandstone. Chemical reduction and precipitation of uranium occurred when these fluids reacted with carbon-rich metasediments of the Koolpin Formation faulted against the sandstone units.

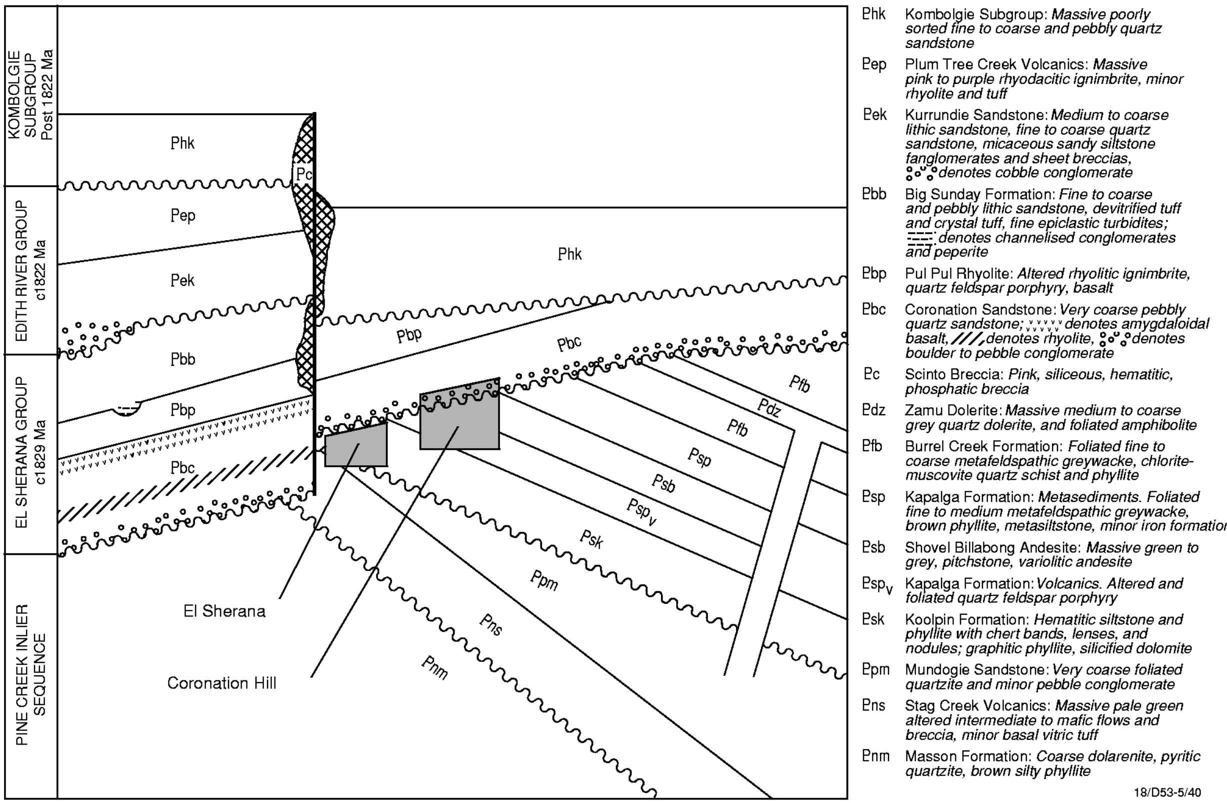

Figure 21. Schematic relationship of the El Sherana and Coronation Hill deposits to the stratigraphic sequence in the South Alligator Valley (modified after Wyborn, 1992; age dates generalised after Jagodzinski, 1999; R.W. Page quoted in Kruse & others, 1994)

Wyborn (1992) and Mernagh and others (1994) proposed that U–Au and Au–Pt–Pd deposits in the South Alligator Valley were formed by descending, low temperature, highly oxidised, very saline meteoric fluids. These fluids descended into fault zones and, at the unconformity, interacted with carbonaceous or chloritic rocks under reducing conditions, causing precipitation of uranium and gold. Where the fluids reacted with feldspathic or carbonate rocks, the resulting increase in pH caused the precipitation of gold, platinum and palladium but not uranium. Hence, uranium deposits occur in carbonaceous shales and cherty ferruginous siltstones, whereas gold–platinum–palladium deposits (e.g. Coronation Hill) occur in a broad range of host rocks including quartz–feldspar porphyry, tuffaceous siltstone, diorite and sedimentary breccia.

Deposits

Virtually all of the uranium production of the South Alligator Valley field was obtained from 13 small deposits in the upper reaches of the South Alligator River valley. Several were on precipitous ridges along the north-eastern side of the valley in a north-west-trending zone 20 km long, from the Rockhole mine in the north-west to Coronation Hill in the south-east. Production was also recorded at the Sleisbeck deposit, in the Katherine River catchment area, about 30 km south-east of Coronation Hill.

At **Rockhole 1**, **Rockhole 2**, **O'Dwyers**, **Sterrets** and **Teagues** (collectively referred to as the Rockhole Group), ore was mined from small zones of high-grade uranium–gold ore along the Palette Fault zone, a steeply dipping reverse fault (Needham, 1987; Valenta, 1991). The fault has thrust Koolpin Formation shale and siltstone up against the Coronation Sandstone, Pul Pul Rhyolite and Kombolgie Subgroup. Small irregular shoots of pitchblende–gold mineralisation from 2 cm to 2 m wide occurred within cherty ferruginous siltstone and carbonaceous shales (Prichard, 1965). In places, mineralisation extended into the sandstone.

At **El Sherana** and **El Sherana West**, uranium–gold mineralisation occurs in two general settings: at or near the shallow-dipping Koolpin Formation/Coronation Sandstone unconformity, where it is cut by normal and reverse faults, e.g. ore in the El Sherana pit. The host rocks are chert-banded siltstone and carbonaceous shale adjacent to sandstone (Coronation Sandstone) and altered volcanics (Pul Pul Rhyolite) (Fig. 21), in irregular zones along the contacts between cherty ferruginous shale and carbonaceous shale, e.g. El Sherana West. The ore zones consisted of massive segregations, veins and disseminations of pitchblende (Taylor, 1968). Gold occurred as veinlets within pitchblende or as separate zones of mineralisation.

At the **Palette** deposit, nodules and veins of pitchblende with associated gold occurred along the Koolpin Formation/Coronation Sandstone unconformity and along fault zones where these two sequences are in contact. Primary mineralisation was pitchblende veins in shears and fractures, and massive nodules in carbonaceous shales, mostly altered to chloritic shale (Needham, 1987). Secondary uranium mineralisation occurred as disseminations in weathered carbonaceous and ferruginous banded shale and siltstone, and Coronation Sandstone. Phosphuranylite and uranophane were the most common secondary uranium minerals. Gold occurred in veins within pitchblende, along with minor pyrite, chalcopyrite and galena.

The **Saddle Ridge** deposit was adjacent to a major east–west-trending reverse fault that separates rocks of the Koolpin Formation from sandstone and ignimbrites of the El Sherana Group. The orebody was mostly within the Koolpin Formation. Mineralisation was irregularly disseminated secondary uranium minerals, mainly metatorbernite.

At the **Coronation Hill** deposit (Fig. 22) there are two general types of mineralisation, which form separate ore zones:

- gold–platinum–palladium,
- uranium–gold (with minor platinum–palladium).

Uranium–gold ore was mined in 1961 and 1962 with a small open cut, and glory hole methods. The average grade of ore mined consisted of 0.26% U_3O_8 and an estimated 10.4 g/t Au. The gold–platinum–palladium orebody was delineated by drilling carried out during 1984–88 by the Coronation Hill Joint Venture (CHJV).

The Coronation Hill area occupies a zone of complex faulting in a large-scale dilational offset on the Palette Fault System (Valenta, 1990). The uranium ore in the old open cut occurs in debris flow breccia and altered rhyolites of the Coronation Sandstone (Needham & Stuart-Smith, 1986). Uranium mineralisation is associated with faulted blocks of carbonaceous shale (Koolpin Formation) within the conglomerate and also with areas where the conglomerate contains abundant clasts of carbonaceous shale (Needham, 1987). The ore zone forms a vertical cylindrical body about 20 m across and consists of pitchblende mineralisation with narrow veinlets and dissemination of gold. Carville and others (1991) noted that the debris flow breccia (referred to as type 'A' and type 'B' breccias) is in fault contact with the adjoining lithologies and is younger than the sandstones of the Kombolgie Subgroup.

The drilling carried out by the CHJV outlined the gold–platinum–palladium orebody, and also intersected a zone of high grade uranium–gold mineralisation approximately 120 m below the old open cut. The ore zone is located in an area of complex faulting and occurs within brecciated chloritic tuffaceous siltstone and carbonaceous siltstones and brecciated quartz feldspar porphyry (Fig. 22). The high-grade mineralisation is best developed where a major fault intersects the unconformity at the base of the Capping Sandstone (Kombolgie sandstone equivalent). In situ indicated resources were estimated to be

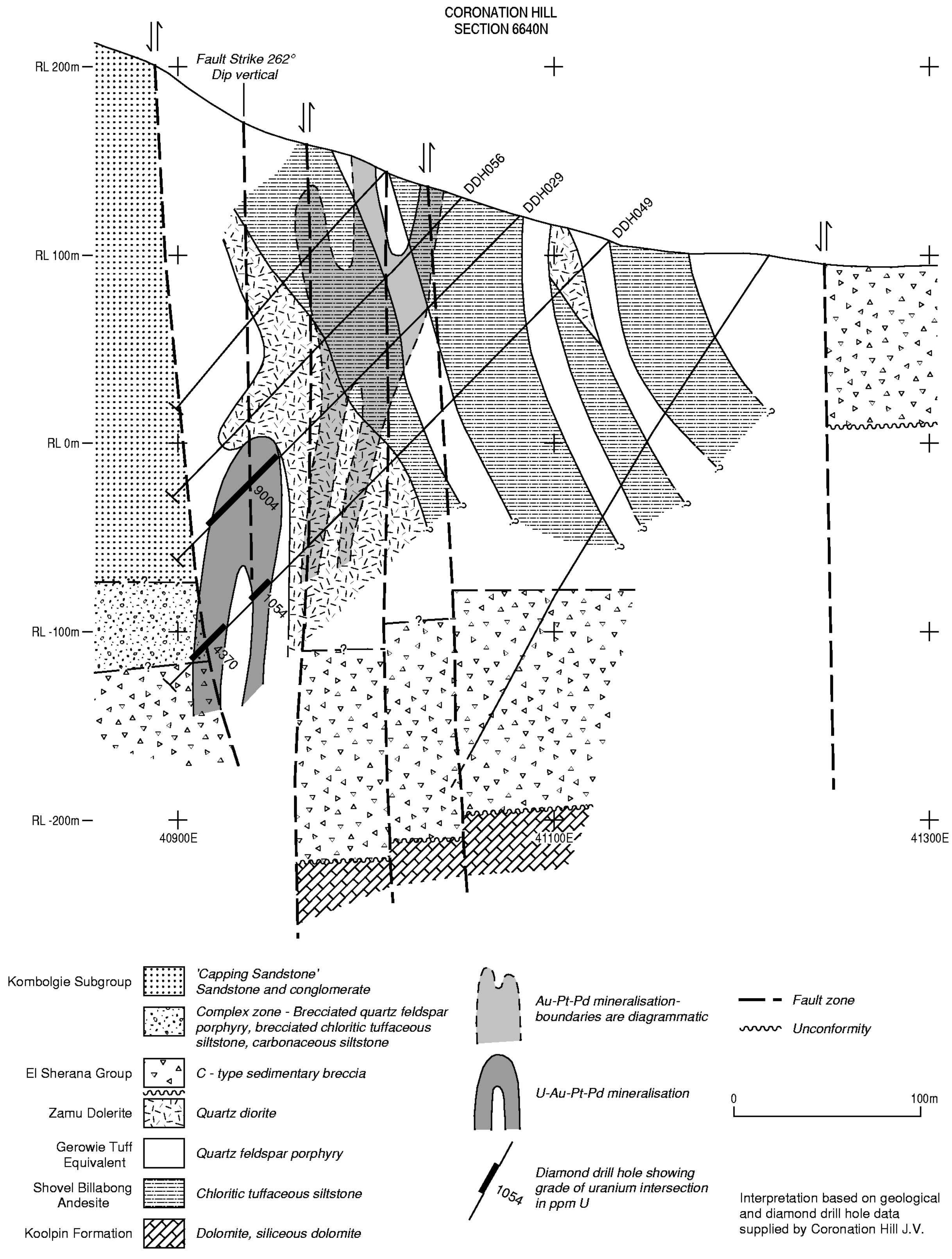

Figure 22. Coronation Hill deposit, cross-section 6640N, showing zones of mineralisation

344 170 t averaging 0.537% U_3O_8 (1850 t U_3O_8) and 9.95 g/t Au. The ore zone is open (untested) to the north and at depth (McKay, 1990).

The gold–platinum–palladium orebody at Coronation Hill occurs in a variety of lithologies and is developed close to the unconformity between the Coronation Sandstone and older pre-1870 Ma basement sequences. The gold–platinum–palladium mineralisation is adjacent to but separate from the uranium-rich zones. The mineralisation occurs in narrow quartz–carbonate–chlorite veins forming a series of sub-vertical bodies that cut across lithological boundaries (Fig. 22). Host rocks include quartz feldspar porphyry, green tuffaceous siltstone, dolomite and carbonaceous shale and sedimentary breccias. The geology and structural setting of the gold–platinum–palladium mineralisation at Coronation Hill have been described in detail by Carville and others (1990), Wyborn and others (1990) and Wyborn (1992).

Total indicated resources were estimated at 3.49 Mt averaging 5.12 g/t Au, 0.21 g/t Pt and 0.56 g/t Pd, using a 1 g/t Au cut-off (Carville & others, 1991).

At **Sleisbeck**, pitchblende occurs in chlorite schist of the Kapalga Formation.

Secondary uranium mineralisation at the **2J** prospect, 30 km north-west of Coronation Hill, is in the Stag Creek Volcanics (Foy & Miezitis, 1977).

About 70% of the uranium production from the South Alligator Valley deposits was pitchblende/uraninite mined from the Koolpin Formation while the remainder was secondary mineralisation from the Coronation Sandstone (Needham, 1987). Secondary uranium minerals included phosphuranylite, metatorbernite, autunite, uranophane, soddyite, gummite and saleeite. Gold was present in most of the deposits and was recovered from El Sherana, El Sherana West, Rockhole Group, Palette and Coronation Hill (Table 12).

OTHER UNCONFORMITY-RELATED URANIUM DEPOSITS AND PROSPECTS IN THE PINE CREEK INLIER

Woolner Granite

The Woolner Granite area (Fig. 9), about 60 km east of Darwin, was explored by PNC Exploration (Australia) Pty Ltd during 1987–89 using a Rum Jungle-style unconformity-related uranium deposit model. Ground magnetics, gravity and SIROTEM techniques were followed by drilling of the various anomalies which intersected Palaeoproterozoic dolomite, dolomitic siltstone and dolomitic metapelites in four drill holes at depths of 45–79 m. It was concluded that the lack of hydrothermal alteration and absence of graphitic lithologies considerably downgraded the prospect and the company relinquished tenure over the area (Dunn, 1989).

The Archaean Woolner Granite occurs as two granitic domes which are concealed by 50–60 m of Cretaceous and Cainozoic sediments. Drill hole data show that the Woolner Granite is unconformably overlain in the west by the Dirty Water Metamorphics of possible Archaean or Palaeoproterozoic age and by the Palaeoproterozoic Koolpinyah Dolomite. The Dirty Water Metamorphics consist of a lower member of arenaceous metasediments and an upper member of argillaceous and iron-rich metasediments and dolomite. Common lithologies of the upper member are various types of chlorite schists and graphitic schists, and some of the iron-rich metasediments contain disseminated magnetite (Pietsch & Stuart-Smith, 1984).

The Pb–U–Th isotope analyses determined a mean age for the Woolner Granite of 2675 ± 15 Ma (McAndrew, Williams and Compston, 1985). McAndrew and others (1985) noted that the Woolner

Granite ranges from granitic schist to gneissic granite, with the most pronounced dynamic metamorphism in the northern part of each dome, and that albitisation is widespread. Individual zircons in the Woolner granitoids contain up to 1% uranium, whereas the granitoids themselves have a mean uranium content of only 2.8 ppm. This is below the average uranium content for granitoids in general and much lower than the mean values of 10, 11 and 13 ppm for granitoids of the Nanambu, Rum Jungle and Waterhouse Complexes. According to McAndrew and others (1985), uraniferous zircons indicate that the Woolner granitoids initially were richer in uranium. These authors suggested that after crystallising under relatively reducing conditions as ilmenite series granitoids, the ilmenite was destroyed by post crystallisation (oxidising) alteration and the uranium was lost. Accordingly, there is limited potential for the formation of unconformity-related uranium deposits in this area.

The potential for unconformity-related uranium deposits cannot be ruled out completely in the Woolner Granite area as it is concealed by younger rocks and is difficult to explore. The depletion of uranium in the Woolner Granite may suggest that the uranium has been removed from the granitoids and concentrated elsewhere under reducing conditions. The source for unconformity-related uranium deposits need not be confined to Archaean granites.

Vein-like uranium deposits in the Pine Creek Inlier

A number of vein-like uranium deposits are present in the Pine Creek Inlier and were previously included in the vein-type category of uranium deposits. All these deposits are within 30 km of the perimeter of the late Palaeoproterozoic cover sandstones. The deposits occur in a variety of different host rocks and one is within volcanics interbedded with the sandstones. It is probable that they were all originally overlain by the sandstones, before the cover sequence was eroded. Vein-like uranium deposits have not been found in the Pine Creek Inlier rocks further away from the cover sandstones. The proximity of these deposits to the late Palaeoproterozoic cover sandstones suggests that they were formed when highly oxidised metal-rich fluids circulated in the cover sandstones, before they had been eroded, and mixed with reduced fluids in the host rocks or with the reduced host rocks themselves. The processes that formed these vein-like uranium deposits are similar to those that formed the unconformity deposits closer to the cover sandstones. The vein-like uranium deposits (Adelaide River, George Creek, Fleur de Lys, Dam and Twin) are described below.

Between 1954 and 1956, small parcels of ore were mined from the Adelaide River, George Creek and Fleur de Lys deposits (Table 13). These three small mines are in the Pine Creek Inlier but are outside the three main uranium fields containing unconformity-related deposits (Fig. 9)

Table 13. Production of uranium ore from vein-like deposits in the Pine Creek Inlier

	Ore (t)	Grade (% U_3O_8)	U_3O_8 (t)
Adelaide River	3861	0.5	19.3
Fleur de Lys	118	0.12	0.1
George Creek	122	0.22	0.3

At the **Adelaide River** and **George Creek** mines, pitchblende, with some pyrite and chalcopyrite, is localised along joints and shear zones in sandstone and siltstone of the Palaeoproterozoic Burrell Creek Formation. Remaining resources at the Adelaide River mine were estimated as 1520 t of broken ore at 0.5% U_3O_8 and 5500 t of possible resource at 0.22% U_3O_8 (Stewart, 1966; Crohn, 1968).

The **Fleur de Lys** mine, 40 km south-east of Adelaide River, contains pitchblende, pyrite, chalcopyrite and chalcocite in the primary zone and torbernite, malachite, azurite and cuprite in the oxidised zone. The mineralisation is in the Howley Anticline, in conformable shear zones, in joints, and along bedding planes of graphitic slate of the Palaeoproterozoic South Alligator Group.

Two small uranium deposits (Dam and Twin) and several uranium occurrences are known in the Allamber area, 35 km north-east of Pine Creek (Fig. 9). These deposits and prospects were discovered by Total Mining Australia Pty Ltd in 1986 (Total Mining, 1986) and the company completed a major program of geochemistry, ground radiometrics and drilling over these deposits through to 1989.

Mineralisation in this area occurs in a large number of narrow, closely spaced, sub-parallel veins and fractures associated with fault zones. The mineralised veins are steeply dipping. Mineralisation is hosted by a sequence of chloritic schists, graphitic schists, carbonaceous schist, dolomite and chert. Most of the mineralised veins are in chloritic schists and graphitic schists. The vein system and the host rocks have been extensively intruded by Palaeoproterozoic granite (?Allamber Springs Granite) and intermediate to basic dykes possibly post-dating the Cullen Batholith. The host rocks have been metamorphosed by these granitic intrusions (Stuart-Smith & others, 1993). The metasediments that host the deposits occupy an embayment along the western margins of the Cullen Batholith. Drill hole intersections and surface mapping indicate that the host rocks probably belong to the Masson Formation (Ferenczi, Ahmad & Bajwah, 1993).

The **Twin** deposit comprises two mineralised systems of veins and fractures. Each system is approximately 50 m wide and they are separated by 50 m of barren schists and dolomites. They have been drilled over a strike length of 150 m. At the **Dam** deposit, the mineralised vein system has been drilled over a strike length of 400 m. Estimates of measured and indicated resources are shown in Table 14.

Table 14. Resources for the Twin and Dam deposits, Allamber area, NT (Berthault, 1988)

		Grade (% eU_3O_8)*	**U_3O_8 (t)**
Twin deposit	Measured	0.1159	190.8
	Indicated	0.1237	113.6
	Total	0.1188	304.4
Dam deposit	Measured	0.1324	242.8
	Indicated	0.1258	199.3
	Total	0.1294	442.1

* eU_3O_8 is equivalent grade measured by down-hole radiometric probe

Primary mineralisation consists of pitchblende and pyrite and this is closely associated with chloritic, sericitic and hematitic alteration. Secondary uranium minerals include bassetite, coffinite and meta-autunite.

Several radioactive occurrences are known in the southern part of the Cullen Granite, near the abandoned Edith River railway siding (Crohn, 1968). Secondary uranium minerals occur in small quartz veins and as disseminations in the Tennysons Leucogranite of the Cullen Batholith (Stuart-Smith & Needham, 1984). The **Edith River** occurrence is 2 km east of the railway siding, and **Tennyson's** and **Hore & O'Connor's** are respectively 4 km south-west and 7 km north-west of the siding. Other uranium occurrences in the Cullen Batholith are at **Yenberrie**, 7 km to the north of the siding, in the Yenberrie Leucogranite, and at **Fergusson River**, 15 km north-west, in the Driffield Granite.

At the **ABC** deposit, 17 km north-east of Katherine township, autunite and phosphuranylite occur in interbedded tuff and amygdaloidal basalt of the McAddens Creek Volcanic Member of the Kombolgie Subgroup. Reserves were estimated as 1990 t ore grading 0.25% U_3O_8 (Stewart, 1966).

RUDALL COMPLEX

Regional geological setting

The Rudall Complex is in the north-western part of the Paterson Orogen (Figs 23 and 24) that is delineated by an arcuate gravity anomaly. The gravity anomaly is less than 100 km wide and extends about 2000 km from the east Pilbara to central Australia (Murray & others, 1997). The north-western part of the orogen includes crystalline rocks of the Palaeoproterozoic Rudall Complex and cover sequences of Neoproterozoic Lamil, Throssell and Tarcunyah Groups (Bagas, Grey & Williams, 1995; Williams & Bagas, 1999; Bagas & others, in press). The sandstone–shale–carbonate succession comprising the Throssell Group unconformably overlies the Rudall Complex (Hickman & Clarke, 1994).

The Rudall Complex was deformed and metamorphosed during the Palaeoproterozoic Yapungku Orogeny, and subsequently deformed in the Neoproterozoic during the Miles and Paterson Orogenies (Bagas & Smithies, 1998). The Palaeoproterozoic orogeny is interpreted in terms of a continental–continental collision that occurred in two events during c. 2015–1800 Ma and 1790–1760 Ma, resulting in the formation of fold-thrust belts and partial melting (Smithies & Bagas, 1997; Bagas & Smithies, 1998; Hickman & Bagas, 1999).

Orthogneiss constitutes more than 50% of the Rudall Complex and was derived by metamorphism of at least two suites of granitoid protoliths. The main protolith was porphyritic granite or monzogranite that intruded partly contemporaneous sedimentary successions between about 1787 Ma and 1765 Ma. An earlier granitic suite, which intruded older metasedimentary rocks, forms part of a complex lithologically layered orthogneiss that crystallised at about 2015 Ma. The deposition of the various metasedimentary rocks of the complex must have therefore been completed before 1765 Ma (Table 15) (Hickman & Bagas, 1999).

Table 15. Subdivisions of the Rudall Complex (Hickman & Clarke, 1994; Bagas & Smithies, 1997; Hickman & Bagas, 1999)

THROSSELL GROUP	Basal member is the Coolbro Sandstone — sandstone, minor siltstone, basal conglomerate	
Unconformity, commonly tectonised		
RUDALL COMPLEX	Orthogneiss	Metamorphosed granitoids (1787–1765 Ma)
	Intrusive contact, tectonised	
	Metasedimentary rocks	Quartzite, quartz–muscovite schist, biotite schist, calc–silicate rock, carbonate, carbonaceous schist, minor chert and BIF (all pre-1765 Ma and some older than 2015 Ma)
	Orthogneiss	Complex lithologically layered orthogneiss, crystallised at about 2015 Ma

The Coolbro Sandstone, the basal member of the Throssell Group, unconformably overlies the Rudall Complex. The Coolbro Sandstone is a sandstone succession, up to 4 km thick, containing lensoidal conglomeratic beds and minor interbeds of thin carbonaceous mudstone and shale. The sandstone and the unconformity surface have been folded and faulted during the Miles and Paterson Orogenies. In some areas, particularly near thrust-fault zones, this folding is very complex. Dating of detrital zircons from the Throssell Group shows that it is younger than c. 1070 Ma (Bagas & others, in press). If the Throssell Group is a correlative of the Lamil Group, which hosts the Telfer gold deposit about 80 km to the north of the Kintyre deposit, as proposed by Bagas & others (in press), the Throssell Group is also older than c. 678 Ma (Bagas, 2000).

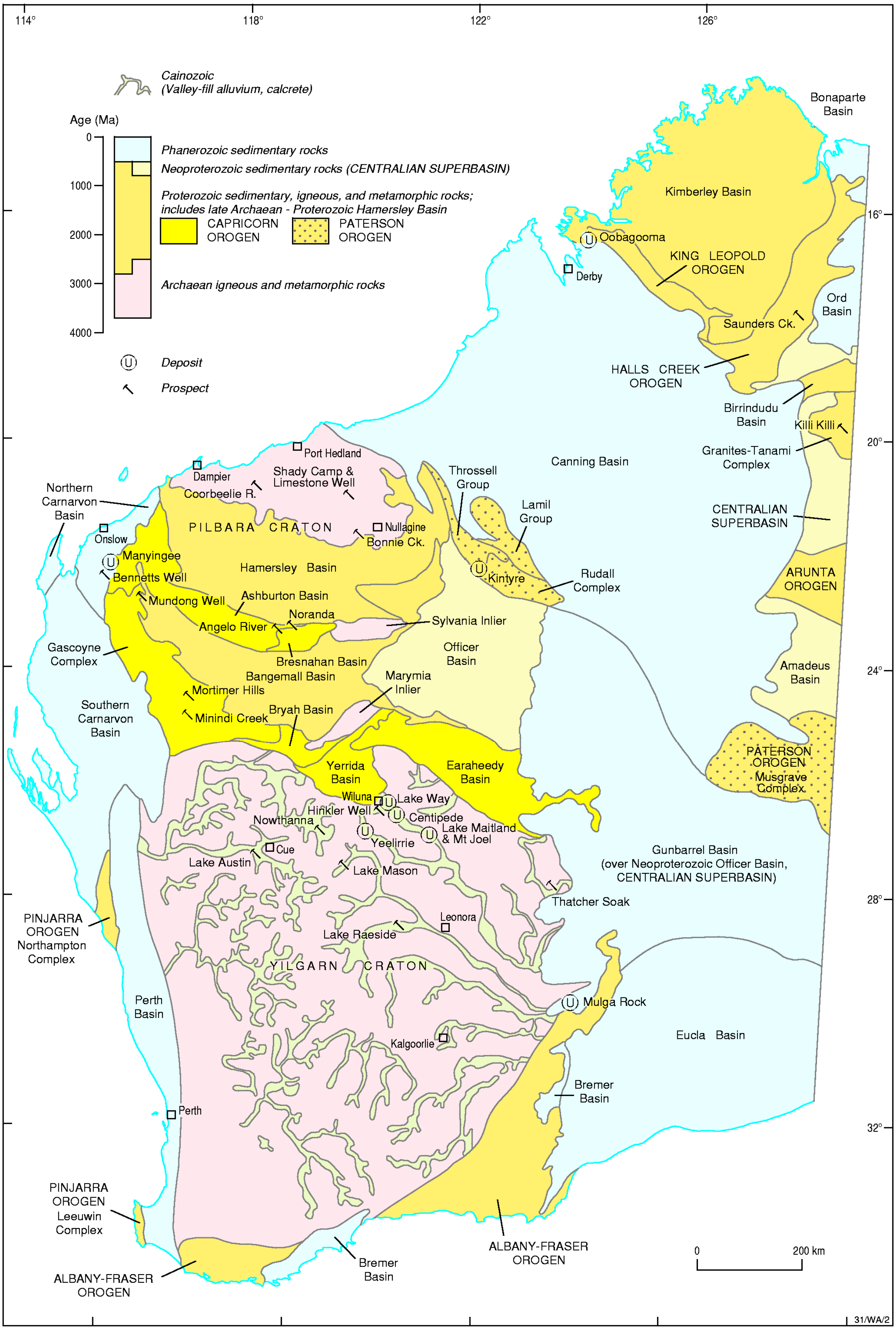

Figure 23. Geological provinces of Western Australia, and locations of uranium deposits and prospects (Tertiary drainage channels are shown only on the Yilgarn Craton). Geological map prepared by Geological Survey of Western Australia.

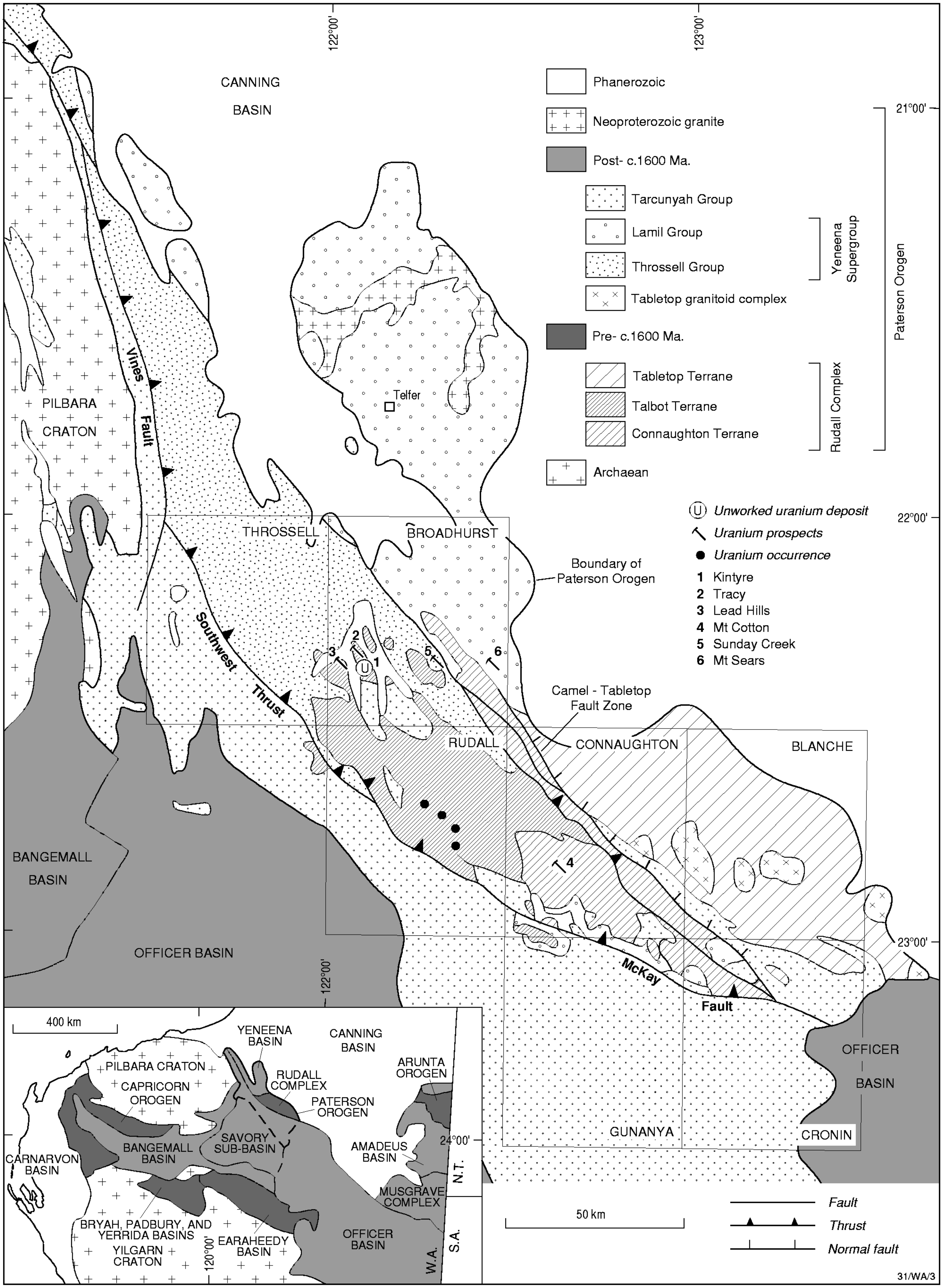

Figure 24. Regional geology of the Rudall Complex and the Yeneena Basin, and locations of uranium deposits and prospects (regional geology after Hickman & Bagas, 1999)

Permian fluvioglacial sandstones and tillite beds of the Paterson Formation unconformably overlie rocks of the north-western part of the Paterson Orogen. These sedimentary rocks fill U-shaped valleys eroded into the pre-Permian land surface (Hickman & Clarke, 1994).

Kintyre deposit

The Kintyre deposit is located about 500 km south-east of Port Hedland, WA (Fig. 23). The deposit was initially within the Rudall River National Park, but in 1994 an area enclosing the deposit was excised from the park.

In 1982 CRA Exploration Pty Ltd (now known as Rio Tinto Ltd) completed an airborne radiometrics and magnetics survey over a portion of the Paterson Orogen as part of an exploration program primarily aimed at locating kimberlites (Jackson & Andrew, 1990). Detailed helicopter-borne surveys were flown over the radiometric anomalies. Follow-up work on one of these led to the discovery in April 1985 of a small area of secondary uranium mineralisation — the surface expression of the Kintyre deposit (Jackson & Andrew, 1988; Root & Robertson, 1994). Drilling of the Kintyre anomaly commenced in October 1985 and the first drill hole intersected 77 m of mineralisation averaging 0.25% U_3O_8. The deposit does not outcrop, and the uppermost parts of the deposit are approximately 50 m below surface. Small amounts of secondary uranium minerals associated with a fault zone occur at the surface.

The Kintyre deposit occurs in metasediments of the Yandagooge Formation in the Rudall Complex adjacent to the unconformity with the Neoproterozoic Coolbro Sandstone (Andrew, 1988; Jackson & Andrew, 1990; Hickman & Clarke, 1994). The metasedimentary rocks were originally an assemblage of limestone, black shale, sandy shale, sandstone and iron formation. The unconformable contact with the Coolbro Sandstone and Rudall Complex is tightly folded and sheared at the deposit, which is hosted by sheared and altered chlorite–garnet–quartz schists in contact with metadolomite and graphitic schist of the Yandagooge Formation (Fig. 25). In the vicinity of the deposit, the Yandagooge Formation is folded into a reclined, gently plunging F_1 antiform (Gauci & Cunningham, 1992; Hickman & Clarke, 1994).

Four events of deformation have been identified in the region. The first two events (D_1, D_2) are included in the Yapungku Orogeny and were associated with the main regional metamorphism of the Rudall Complex that locally reached the granulite facies (Bagas & Smithies, 1998). The third and fourth events (D_3, D_4) have been included in the Neoproterozoic Miles Orogeny (Bagas & Smithies, 1998), which have folded and faulted both the Rudall Complex and Coolbro Sandstone.

Permian glacial tillite beds overlie the eastern portion of the Kintyre deposit.

Pitchblende mineralisation occurs within a system of narrow closely spaced veins which strike north-west and dip 60º north-east. These veins lie along the cleavage of a major north-west shear zone which has faulted the Coolbro Sandstone. This shear is associated with the Miles Orogeny. Multiple sets of closely spaced mineralised veins form ore zones (Fig. 25). The favourable lithologies for mineralisation are interbedded chlorite schist and chert. Mineralisation is best developed where the cleavage intersects chlorite schist at high angles. Pitchblende within these veins often has a colloform texture (Jackson & Andrew, 1990).

The age of the Kintyre mineralisation is uncertain. The deposit is within a shear zone that post-dates the Coolbro Sandstone; hence it appears that the age of the Kintyre mineralisation is younger than 1070 Ma (maximum age of the Coolbro Sandstone).

The ore zones are grouped into five ore bodies, which together comprise the Kintyre deposit. These are the Kintyre and East Kintyre, Whale, East Whale, Pioneer and Nerada deposits (McKay, 1992).

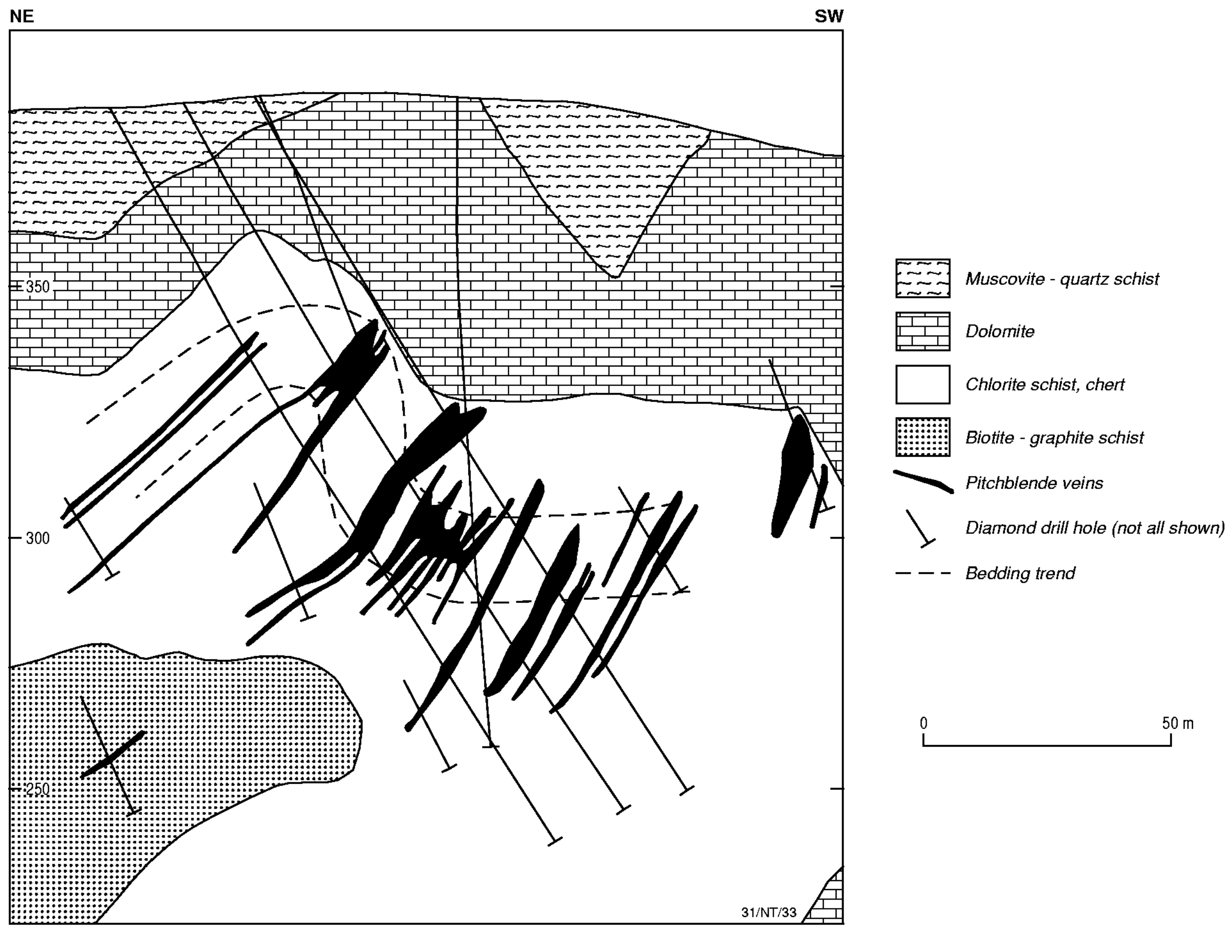

Figure 25. Section through the Kintyre deposit, drawn looking to south-east. The section is at right angles to the veins and oblique to the strike of metasediments and the drilling grid (after Gauci, 1997).

Very minor amounts of bismuth, bismuthinite, chalcopyrite, bornite, galena and gold are associated with the pitchblende veins, whereas chlorite, dolomite, ankerite and calcite are the main gangue minerals. Chlorite alteration is widespread within the metasedimentary rocks enclosing the ore zones, and cherts are red–brown in colour due to the development of hematite (Jackson & Andrew, 1990).

Accurate definition of the resource using drilling data is difficult because of the vein-type mineralisation and the fact that the primary mineralisation does not outcrop. To obtain more detailed information on the mineralisation a small shaft was sunk during 1996, and a drive and a cross-cut were mined through the orebody. The purpose of this was to:

- see the mineralisation and assess its nature and continuity;
- identify the structural controls on the vein system;
- compare grade estimates from drill holes with grades from bulk sampling;
- compare radiometric measurements and chemical assays; and
- provide a bulk sample for metallurgical purposes.

The results from detailed underground mapping, channel sampling and horizontal drilling from the underground openings has provided a more accurate picture of the mineralisation and resulted in a reinterpretation of the geological model. This has defined new targets for exploration and has shown that extra data are required to more accurately plan an open cut mining operation (Larson, 1997; McKay, 1998).

The Kintyre deposit is estimated to have a ‘probable resource’ of 24 500 t U_3O_8, with an additional inferred resource of 11 500 t U_3O_8 (Gauci & Cunningham, 1992). The average grade for the mineralisation ranges between 0.15% and 0.4% U_3O_8.

Other prospects

Uranium mineralisation at the **Tracy** and **Lead Hills** prospects (Fig. 24) is associated with copper, lead and zinc in veins within schist of the Rudall Complex (Hickman & Clarke, 1994). Exploration by CRA indicates that Lead Hills is geologically similar to Kintyre.

At the **Mount Cotton** prospect, which is located about 75 km to the south-east of the Kintyre deposit, uranium mineralisation occurs in veins within graphite–garnet–chlorite schists (Bagas, Williams & Hickman, 2000). The best drill intersection is 0.34 m averaging 1.5% U_3O_8 (Andrew, 1988).

Occidental Minerals Corporation of Australia discovered U–Cu mineralisation within the Coolbro Sandstone at the **Sunday Creek** and **Mt Sears** prospects, which are located about 30 km and 50 km to the east of the Kintyre deposit, respectively. Drilling at Sunday Creek intersected narrow zones of mineralisation within sandstone (Swingler, 1981) whereas at Mt Sears pitchblende mineralisation is in a shear zone within sandstone units at the top of the Coolbro Sandstone (Schwabe, 1981). This shows that the uranium mineralisation must be younger than 1070 Ma which is the maximum age for the Coolbro Sandstone.

TUREE CREEK AREA

The Turee Creek area lies along the boundary between the Ashburton and Bresnahan Basins, 1200 km north-north-east of Perth (Fig. 23). In 1972, Noranda Australia Ltd conducted an airborne radiometric survey along the Palaeo/Mesoproterozoic unconformity in the search for unconformity-related uranium deposits of the Alligator Rivers type. A strong radiometric anomaly was outlined over secondary uranium mineralisation in Mesoproterozoic sedimentary strata of the Bresnahan Basin, about 16 km north-north-west of Turee Creek Station. Between 1973 and 1981, the prospect was investigated and drilled in an unsuccessful attempt to locate primary uranium mineralisation at depth near the Palaeo/Mesoproterozoic unconformity.

Uranium mineralisation in the Angelo River area, 60 km west of Turee Creek Station, was discovered during exploration carried out by a joint venture between Pancontinental Mining NL, PNC Exploration (Australia) Ltd and Minatome Australia Pty Ltd. The prospect was found during follow-up work on airborne radiometric anomalies and occurs at a contact between Mesoproterozoic sandstone and Palaeoproterozoic shale, greywacke and dolomite of the Mount McGrath Formation (Wyloo Group). The most significant mineralisation was found in 1980–81 (Lustig & others, 1984).

Regional geological setting

In the Turee Creek area, Palaeoproterozoic metasediments of the Wyloo Group form a trough, the Ashburton Basin, along the south-western margin of the Hamersley Basin. Wyloo Group sediments are unconformably overlain by a thick sequence of unmetamorphosed arenitic clastics of the Mesoproterozoic Bresnahan Group (Fig. 23) (Lustig & others, 1984; Thorne, 1990).

The Wyloo Group, near the Angelo River prospect, consists, in ascending stratigraphic order, of greywacke, shale, dolomite and carbonaceous shale of the Mount McGrath Formation, followed by dolomite and dolomitic shale of the Duck Creek Dolomite, which in turn are overlain by interbedded shale, siltstone and greywacke of the Ashburton Formation. The Wyloo Group was folded and metamorphosed to greenschist facies at 1800–1700 Ma.

The Bresnahan Group, to the east, comprises three major facies associations: valley-fill, alluvial-fan channel and lacustrine.

Prospects

The **Angelo River** prospect consists of two mineralised zones, 2 km apart — the Angelo A-zone to the west and the Angelo B-zone to the east (Lustig & others, 1984). Uranium occurs along a north-east-trending normal fault that separates the upper part of the Mount McGrath Formation from the sandstones of the upper Bresnahan Group.

The Angelo A-zone is a small deposit of 643 000 t grading 0.124% U_3O_8. It is about 400 m long, with a maximum thickness of about 30 m. Uranium mineralisation is hosted by hematitic and/or carbonaceous shale, their brecciated equivalents, and chert breccia that forms a sequence of uncertain age within the contact zone.

The Angelo B-zone was found in 1980. Mineralisation has a maximum width of 8.5 m and an average grade of 0.047% U_3O_8. The host rock is clay, carbonaceous in part, and brecciated sandstone. The U–Pb isotope data from the deeper part of the B-zone indicate that the age of U mineralisation is about 1015 ± 30 Ma (Lustig & others, 1984). Uraninite, carnotite, phosphuranylite and metatorbernite have been identified from the Angelo A-zone and B-zone.

Petrological, geochemical and stable-isotope studies of the host rocks indicate that uranium has been syngenetically enriched in some shales and carbonaceous shales of the Mount McGrath Formation (Ewers & Ferguson, 1985; Thorne & Seymour, 1991). According to Ewers and Ferguson (1985), near-surface oxidising acid fluorine-bearing groundwaters may have leached uranium from the syngenetically enriched rocks. These groundwaters were neutralised and buffered through wall-rock reactions in the fault zones, particularly in the vicinity of dolomites, resulting in deposition of uranium and further concentration, mainly as secondary phosphate minerals, in late fractures post-dating the main brecciation.

The **Noranda** prospect found by Noranda Australia Ltd is 16 km north-north-west of Turee Creek Station in arkose of the Bresnahan Group. The prospect lies within the Bresnahan Basin, where the Kunderong Sandstone is underlain by the Woongarra Volcanics of the Hamersley Basin. A body of 500 000 t of secondary uranium mineralisation, grading slightly less than 0.05% U_3O_8, lies at least 200 m above the Palaeo/Mesoproterozoic unconformity; it is not known whether this deposit was derived from an unconformity-related primary source. The ore minerals are uranyl phosphates and silicates (C.P. Pedersen, Noranda Australia Ltd, personal communication 1984; Noranda Pacific Ltd, 1985).

Some minor occurrences of uranium have been located in the Palaeoproterozoic Wyloo Group, but none has been reported to be of commercial significance. Other minor occurrences of uranium mineralisation have been recorded at several places (Carter, 1981) in the Bresnahan Group and are regarded as sandstone-type mineralisation rather than unconformity-related.

Cooper, Langford and Pirajno (1998) have reported that some of the uranium occurrences may be of unconformity-related type; they occur near the unconformity between the Bangemall Basin sequence and the underlying basement rocks of the Palaeoproterozoic Gascoyne Complex and the Archaean Sylvania Dome.

Granites–Tanami Inlier

Past exploration for unconformity-related uranium deposits has been along the unconformable contact between the deformed Archaean–Palaeoproterozoic basement rocks and the overlying sandstones and conglomerates of the Birrindudu Group (Blake & Hodgson, 1975; Western Australia Department of Mines, 1980; Carter, 1981). The geological framework of the region is still being reinterpreted and the latest summary outlined here is according to Hendrickx and others (2000).

The Archaean gneiss and schist of the Billabong complex and Browns Range Metamorphics represent the oldest rocks of the basement. The oldest Palaeoproterozoic sequence is the MacFarlane Peak Group, which formed during an early rift stage and comprises mafic volcanic and volcaniclastic rocks, minor clastic sediments and calc-silicate rocks. These rocks are overlain by clastic sediments of the Tanami Group representing a thick passive margin sequence. The lower part of the sequence contains carbonaceous siltstone with minor banded iron formation and calc-silicate rocks of the Dead Bullock Formation succeeded by turbiditic sediments of the Killi Killi Formation. A ferruginous chert unit is interpreted to occur either at or near the top of the Killi Killi Formation (Hendrickx & others, 2000).

The MacFarlane Peak Group and the Tanami Group were intruded by dolerite sills followed by a major deformation, greenschist to amphibolite metamorphism and intrusion of the Inningarra Suite of granites at about 1840 Ma. This was followed by localised extension and formation of small basins filled with shallow marine sediments of the Pargee Formation in the west and with pillow lavas and turbiditic sediments of the Mount Charles Formation in the east. During 1830–1810 Ma the region was intruded by at least three suites of granite accompanied by two phases of volcanism. Deformation of these rocks was followed by the intrusion of another suite of granites during 1800–1795 Ma. During, perhaps, ~1790–1700 Ma, a 2 km thick sequence of quartz arenite with minor carbonate of the Birrindudu Group was deposited over the basement rocks.

The **Killi Killi No. 1 and No. 2** uranium prospects (Fig. 23) are in coarse lithic arenite and conglomerate within the basal 6 m of the Gardiner Sandstone at the base of the Birrindudu Group (Blake, Hodgson & Muhling, 1979). At the No. 1 prospect, anomalous radioactivity persists along the strike for about 1350 m. Samples showing maximum radioactivity gave analytical results of 0.18% and 0.23% U_3O_8. The main uranium-bearing mineral is xenotime, a rare-earth–uranium phosphate.

At **Mount Junction**, ferruginous chert with anomalous uranium and copper is associated with altered volcanic rocks and shale of the Tanami Group (Pearcey, Kepert & Rothchild, 1988 in Hassan, 2000).

The **Don** uranium and gold occurrence was located during extensive radiometric and geobotanical exploration (1980 to 1984) for unconformity-related uranium between the Gardiner Sandstone and the underlying Palaeoproterozoic and Archaean rocks (Hassan, 2000).

Other uranium occurrences in the Granites–Tanami Inlier include **Mount Mansbridge**, **Birrindudu 2**, **Jaimani** and **Oracle** (Hassan, 2000).

Halls Creek area

In the Halls Creek area (WA) there has been extensive exploration for unconformity-related uranium mineralisation. Exploration concepts followed the unconformity-related uranium model of the Pine Creek Inlier and the favourable target area was the unconformity between the Kimberley Group sediments and the deformed basement of the Lamboo Complex.

The Halls Creek Orogen developed during the Palaeoproterozoic between a postulated Kimberley Craton of possible late Archaean age underneath the Kimberley Basin in the north-west and a composite Archaean–Palaeoproterozoic North Australia Craton to the south-east. The orogenic belt strikes north-east and includes the Eastern, Central and Western zones of the Palaeoproterozoic Lamboo Complex, with associated granitoids and mafic–ultramafic intrusions and deformed margins of overlying Palaeoproterozoic to Palaeozoic sedimentary basins (Sanders, 1999). The tectonic reactivation of the orogen continued periodically throughout the Mesoproterozoic, Neoproterozoic and Phanerozoic (Thorne & Tyler, 1996 in Sanders, 1999).

The Eastern zone consists of low- to medium-grade metasedimentary and meta-igneous rocks of the Halls Creek Group (c. 1880–1840 Ma), which unconformably overlie bimodal volcanic rocks of the Ding Dong Downs Volcanics (c. 1910 Ma) and the granitoids of the Sophie Downs suite (1910 Ma). The main components of the Central zone are banded and migmatitic pelitic and psammitic gneiss, marble, calc-silicate rock and mafic granulite of the Tickalara Metamorphics (maximum depositional age of 1865 Ma). These metamorphics have been intruded by sheet-like granitoids of the Dougalls suite (c. 1850 Ma) and at least three major generations of layered mafic–ultramafic intrusions ranging in age from c. 1855 Ma to 1830 Ma (Page & Hoatson, 2000). The southern part of the Central zone is occupied mainly by felsic volcanics, epiclastic sediments, mafic volcanics, interbedded cherts, banded iron formations and carbonate of the Koongie Park Formation. The Western zone consists of a turbiditic succession of thinly bedded metamorphosed mudstone, siltstone and quartz wacke of the Marboo Formation which has been intruded by the granitoids of the Paperback supersuite (1865–1850 Ma). In the southern part of the zone, paragneiss and orthogneiss of the Amherst Metamorphics are considered to be protoliths of the Marboo Formation and the Paperbark supersuite. The Marboo Formation is unconformably overlain mostly by felsic porphyry and minor pyroclastics, basalt and volcaniclastic metasedimentary rocks of the Whitewater Volcanics.

The granitoids in the Lamboo Complex have been divided into Sophie Downs suite (c. 1910 Ma), Dougalls suite (c. 1850 Ma), Paperback supersuite (1865–1850 Ma), Sally Downs supersuite (1835–1805 Ma) and Mas San Sou suite (1805–1790 Ma).

Layered mafic–ultramafic intrusions are confined to the Central and Western zones of the Lamboo Complex. The intrusions were emplaced in three main episodes between 1855 Ma and 1805 Ma (Page & Hoatson, 2000).

The western margin of the Lamboo Complex is overlain by Palaeoproterozoic metasediments of the 1835 Ma Speewah Group and the Kimberley Group. The eastern margin of the Lamboo Complex is overlain by Neoproterozoic Albert Edward Group, the Duerdin Group and by the Neoproterozoic to Palaeozoic sedimentary rocks and the Antrim Plateau Volcanics of the Ord River Basin.

The **Amphitheatre** uranium–copper prospect occurs in metasedimentary rocks of the Koongie Park Formation, immediately below an angular unconformity with overlying quartz sandstone of the King Leopold Sandstone at the base of the Kimberley Group. A very narrow carnotite-bearing ferruginous clay-rich zone assayed 0.27% U.

At **Mad Gap** prospect, minor uranium mineralisation occurs at several locations in sediments near the base of the Speewah Group above an unconformable contact with the underlying White Water Volcanics (Sanders, 1999).

TENNANT CREEK AREA

The Palaeoproterozoic Tennant Creek Inlier consists of three distinct provinces; from north to south they are the Ashburton province, the Central province (previously known as Tennant Creek Block) and the Davenport province in the south (Le Messurier, Williams & Blake, 1990; Donnellan, Morrisson & Hussey, 1994; Stolz & Morrison, 1994; Compston, 1995; Donnellan, Hussey & Morrisson, 1995; Ferenczi & Ahmad, 1998). The Central province has the most mineralisation of the three provinces with numerous gold deposits with varying amounts of copper and bismuth. The Davenport province has small tungsten, gold, copper, silver/lead and uranium occurrences while Ashburton province lacks any significant mineral occurrences. The Palaeoproterozoic Warramunga Group which forms the major part of the Tennant Creek Block is a sequence of greywacke, siltstone, shale, argillaceous banded iron formation and interlayered felsic volcanics. These rocks are metamorphosed to lower greenschist facies. Isolated occurrences of gneissic rocks have been interpreted as basement, possibly of Archaean age.

To the north, the Central province is unconformably overlain by a thick sequence of Mesoproterozoic quartz sandstone, siltstone and shale of the Tompkinson Creek Beds; and to the south the Central province is unconformably overlain by a thick sequence of Mesoproterozoic clastic sediments and interbedded felsic and mafic volcanics of the Hatches Creek Group.

At the **North Star** mine and the **Edna Beryl** prospect, approximately 40 km north of Tennant Creek, uranium is associated with gold in hematitic shale of the Warramunga Group (Ingram, 1974). The unconformity at the base of the Tompkinson Creek Beds is 5 km north of these zones of uranium mineralisation.

At the **Munadgee** prospect, 85 km south-east of Tennant Creek, secondary uranium mineralisation occurs in sheared and altered feldspar porphyry (?Palaeoproterozoic) which is inferred to intrude into the Warramunga Group. The prospect is near the unconformity at the base of the overlying sediments of the Hatches Creek Group (Blake & others, 1987). The best grade of ore in the old mine workings is 0.82% U_3O_8 over 1.2 m at a depth of 40 m.

EYRE PENINSULA

Archaean granulite facies gneiss of the Sleaford Complex occurs along the western half of the Eyre Peninsula (SA). Palaeoproterozoic metasediments of the Hutchison Group and Palaeoproterozoic granitoids of the Lincoln Complex occur along the eastern portion of the peninsula. The main rock types of the Hutchison Group are quartzite with local quartz-pebble conglomerate, carbonate, iron formation, amphibolite and pelitic schist which have been intensely deformed and metamorphosed to upper amphibolite facies (Parker, 1990; Drexel & others, 1993). The Archaean and Palaeoproterozoic metamorphic rocks are unconformably overlain by flat-lying sandstone of the Corunna Conglomerate.

Exploration for unconformity-related uranium mineralisation in the area around Cleve was carried out in the late 1970s and early 1980s (South Australia Department of Mines and Energy, 1985). At the **Ben Boy** prospect, 12 km east of Cleve, uranium mineralisation occurs in faulted iron formation (Hutchison Group) close to the unconformity at the base of the Corunna Conglomerate (Parker, 1983; Parker, personal communication, 1994). Uranium is associated with copper mineralisation at the **Calcookara** deposit (24 km east-north-east of Cleve), **Poonana** and **Emu Plain** deposits (4 km and 13 km north-north-east, respectively, from Cleve) (Parker, 1983). Mineralisation is in amphibolite, banded iron formation and calc-silicate rocks of the Hutchison Group. These deposits were mined in the past for copper. Small uranium prospects occur in Lincoln Complex granitoids near Port Lincoln (Johns, 1961).

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.

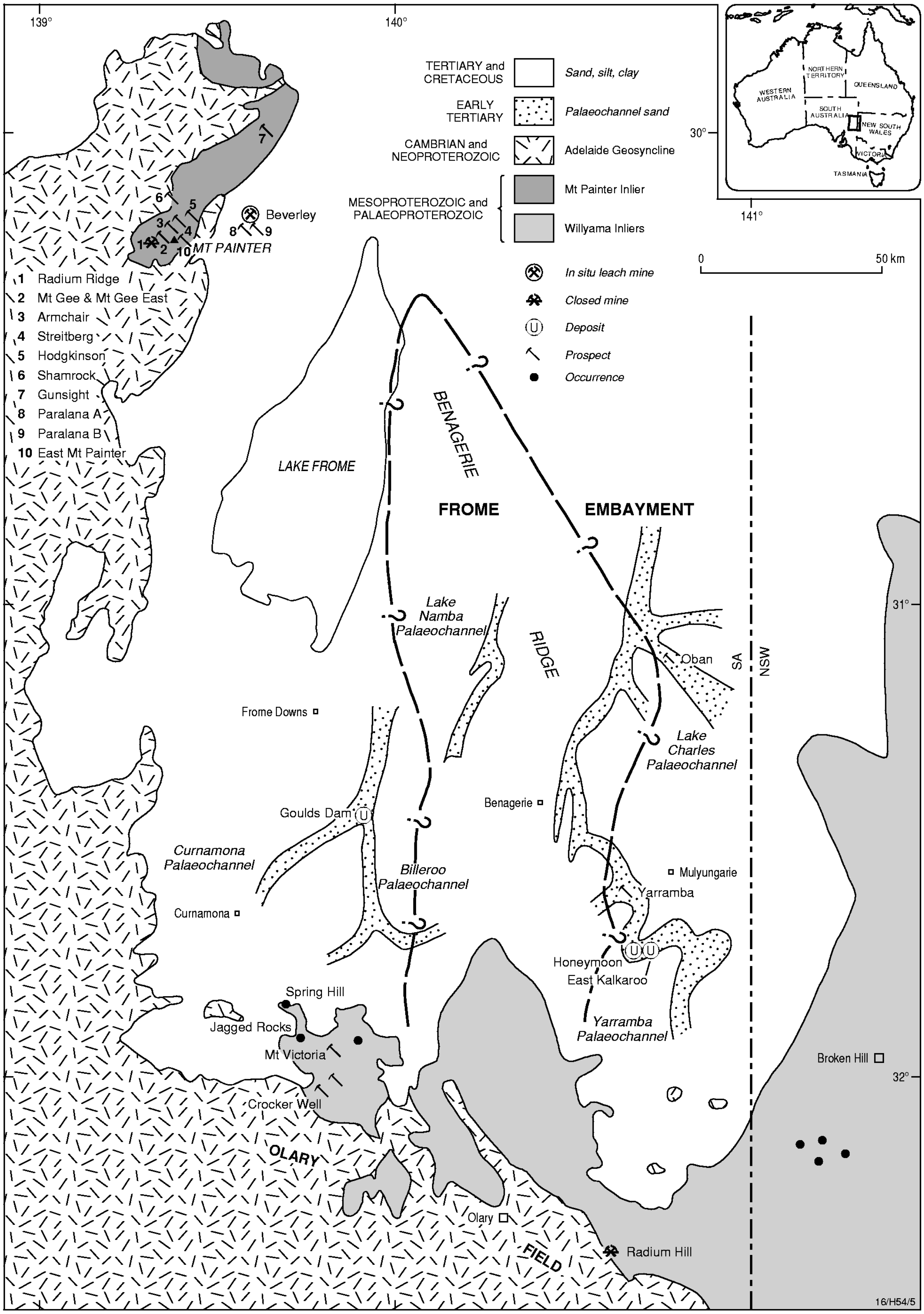

Figure 26. Regional geology of the Frome Embayment and environs showing Tertiary palaeochannels and uranium deposits, prospects and minor occurrences (locations of palaeochannels after Curtis, Brunt & Binks, 1990)

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

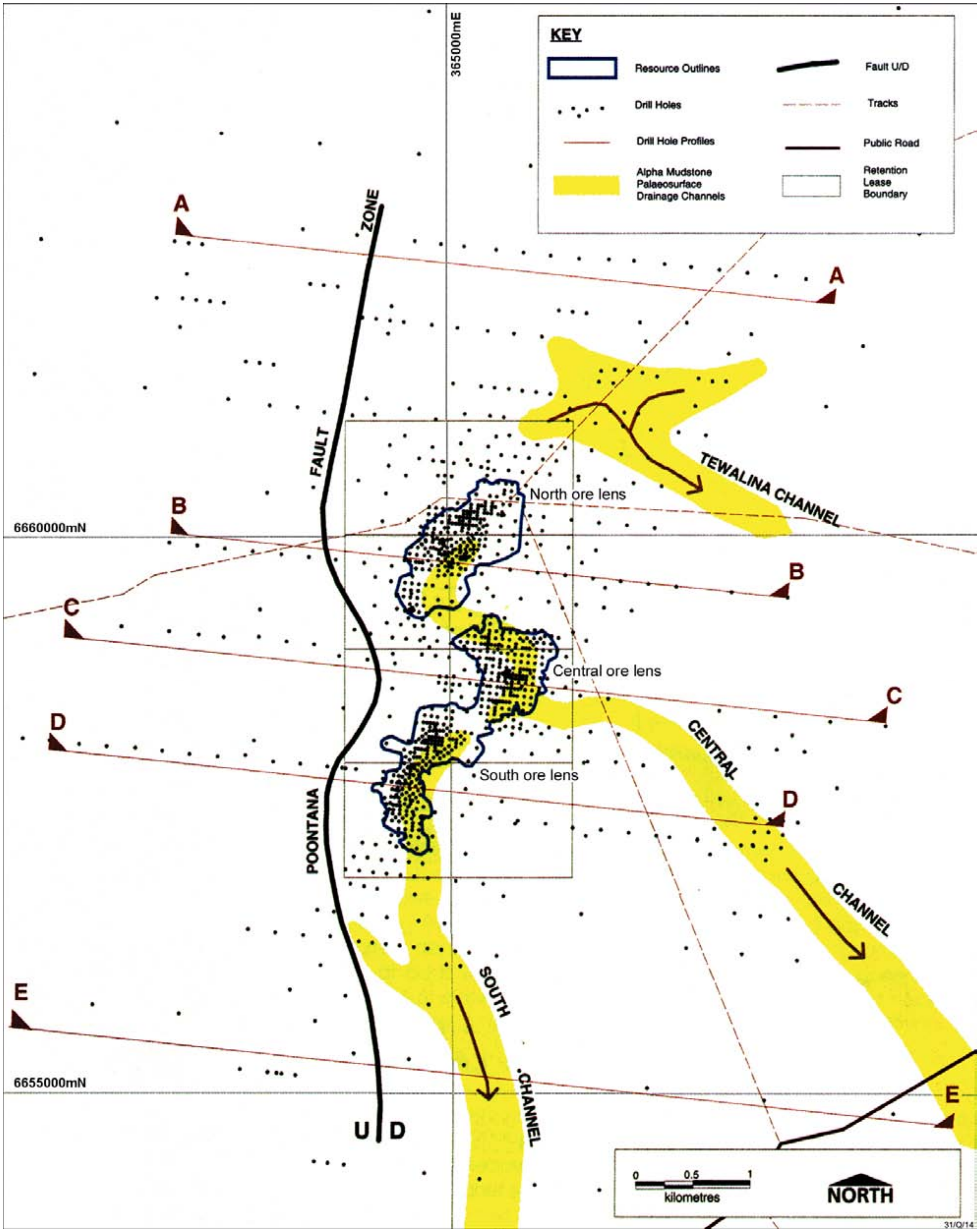

Figure 27. Plan showing Beverley ore lenses, palaeochannels and Poontana fault zone (after Heathgate, 1998)

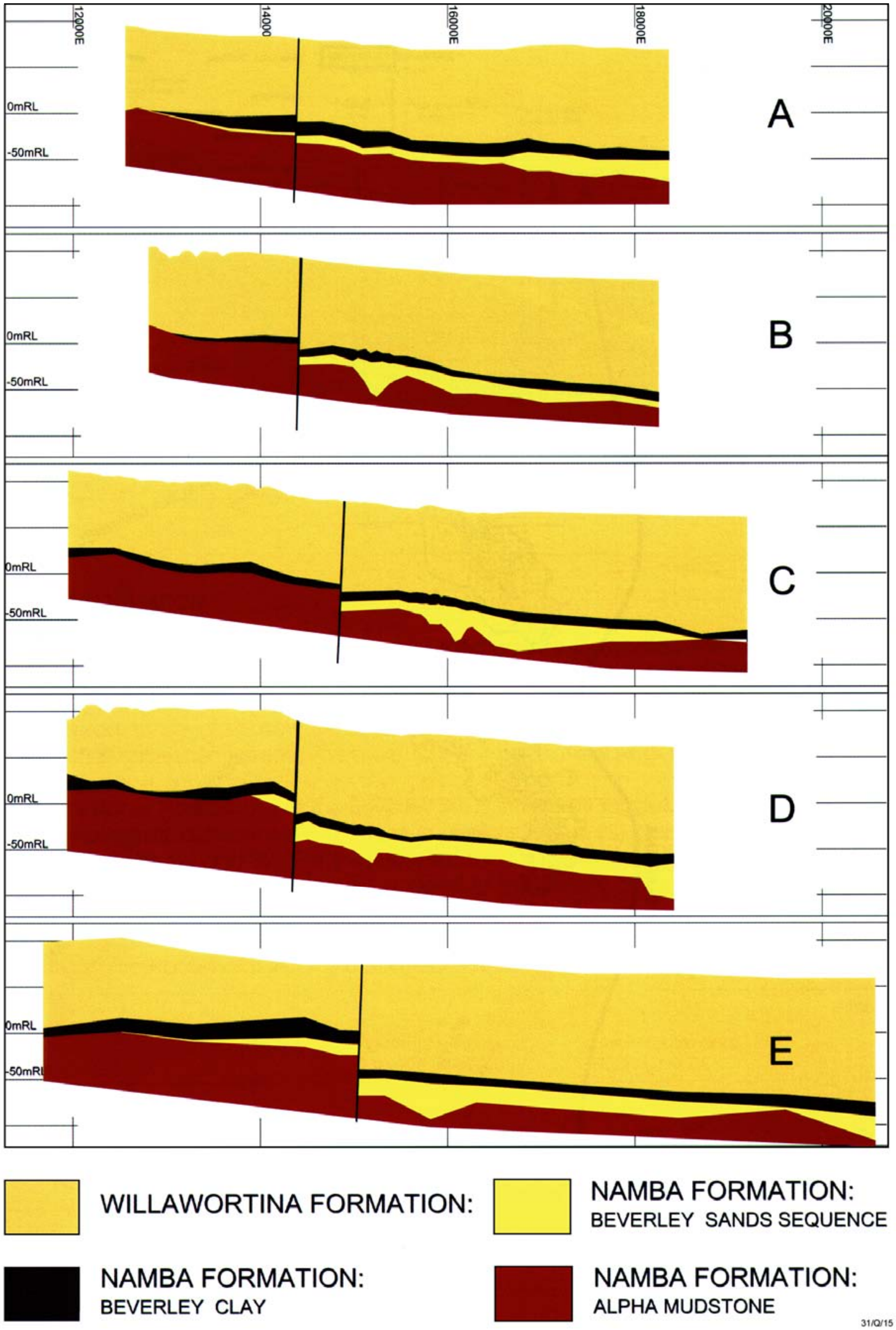

Figure 28. Cross-section through the Beverley aquifer (after Heathgate, 1998)

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.

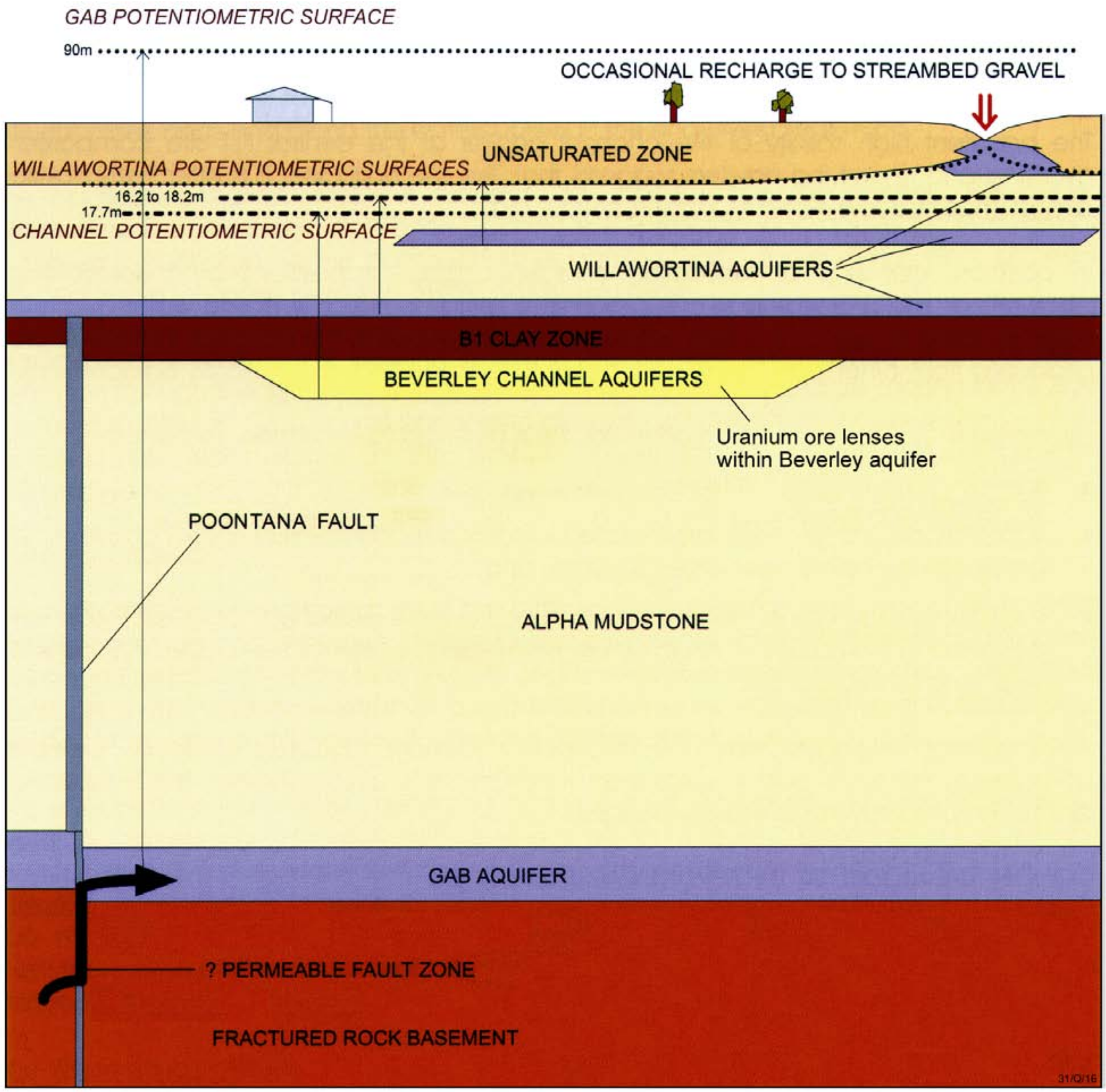

Figure 29. Hydrogeology model in the vicinity of the Beverley palaeochannel (after Heathgate, 1998); GAB stands for Great Artesian Basin; B1 Clay stands for Beverley Clay

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).

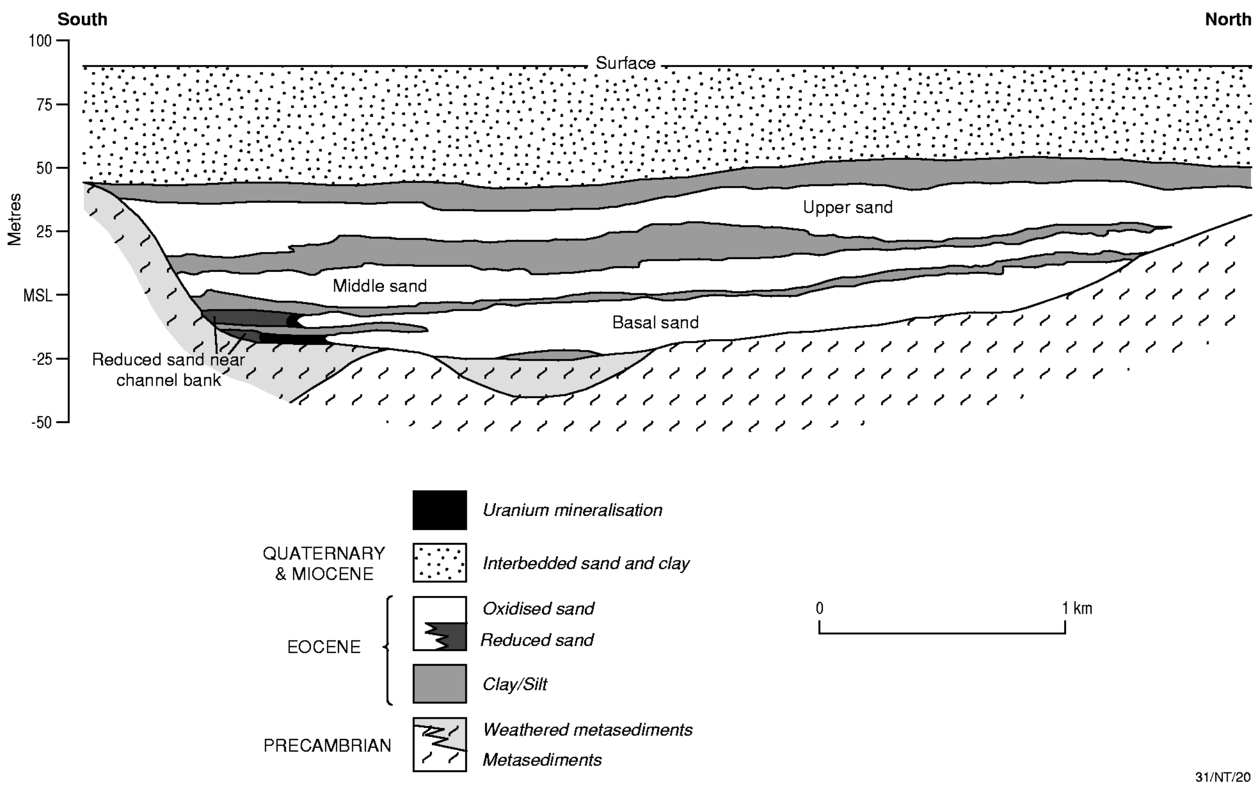

Figure 30. Diagrammatic cross-section through the Yarramba Palaeochannel and Honeymoon deposit (after Southern Cross, 2000); MSL stands for mean sea level

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

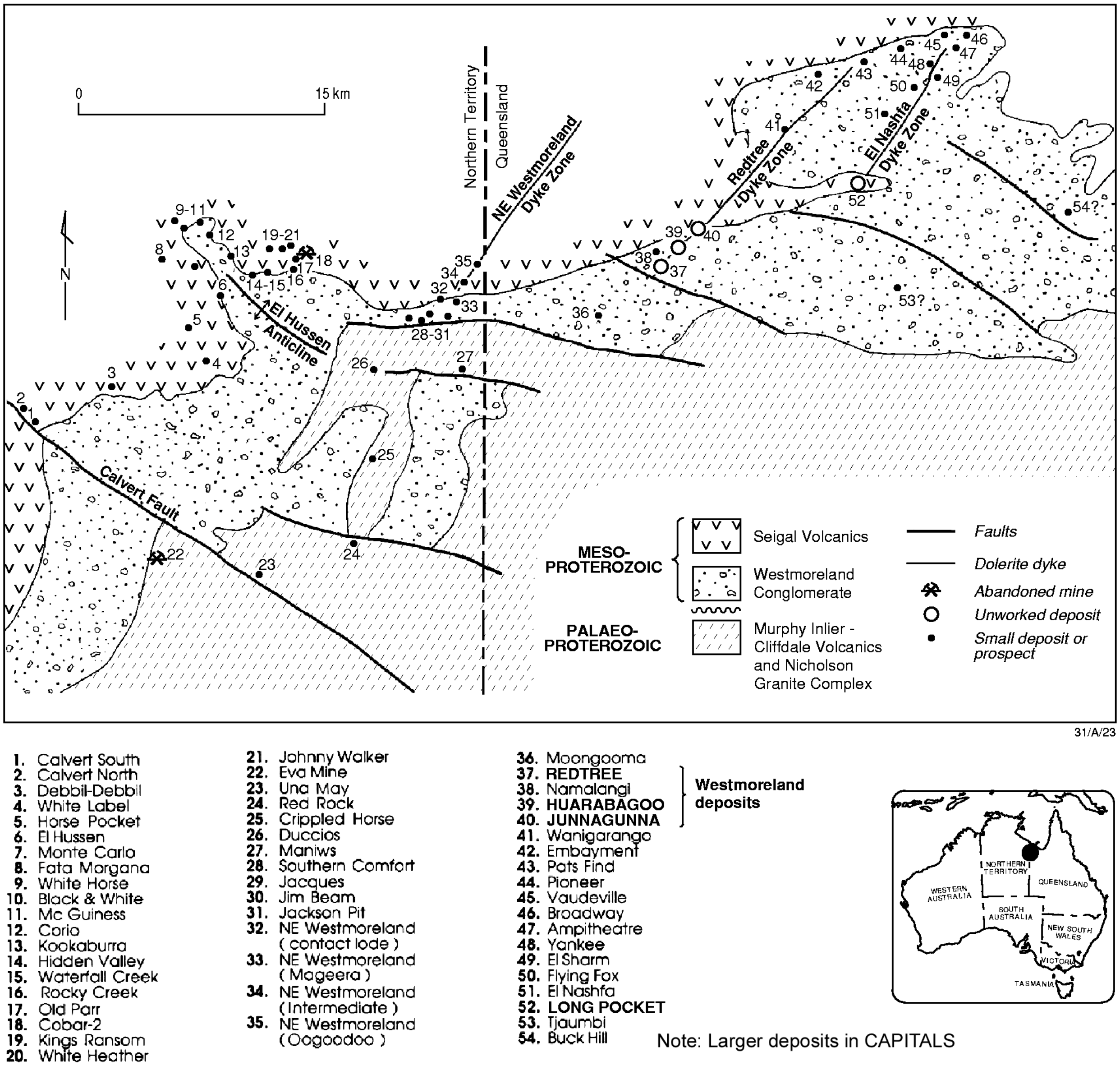

Figure 32. Geological setting of uranium deposits and prospects in the Westmoreland–Pandanus Creek uranium field (after Ahmad & Wygralak, 1989)

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.

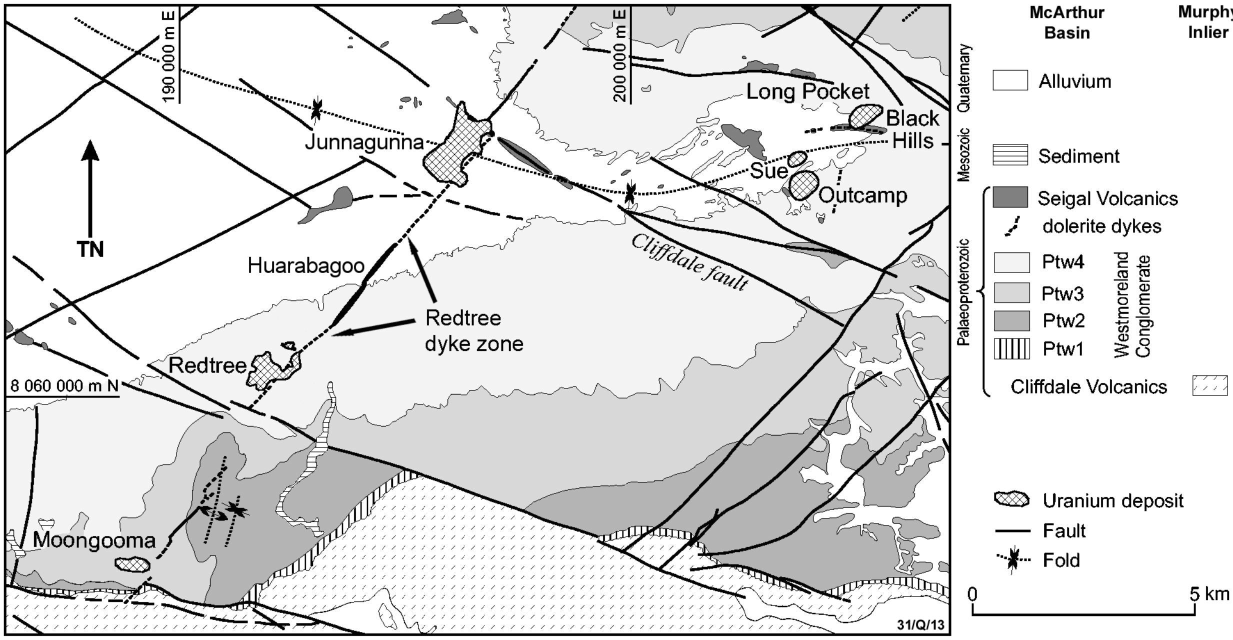

Figure 33. Geology of the Westmoreland uranium deposits (after Rheinberger, Hallenstein & Stegman, 1998)

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.

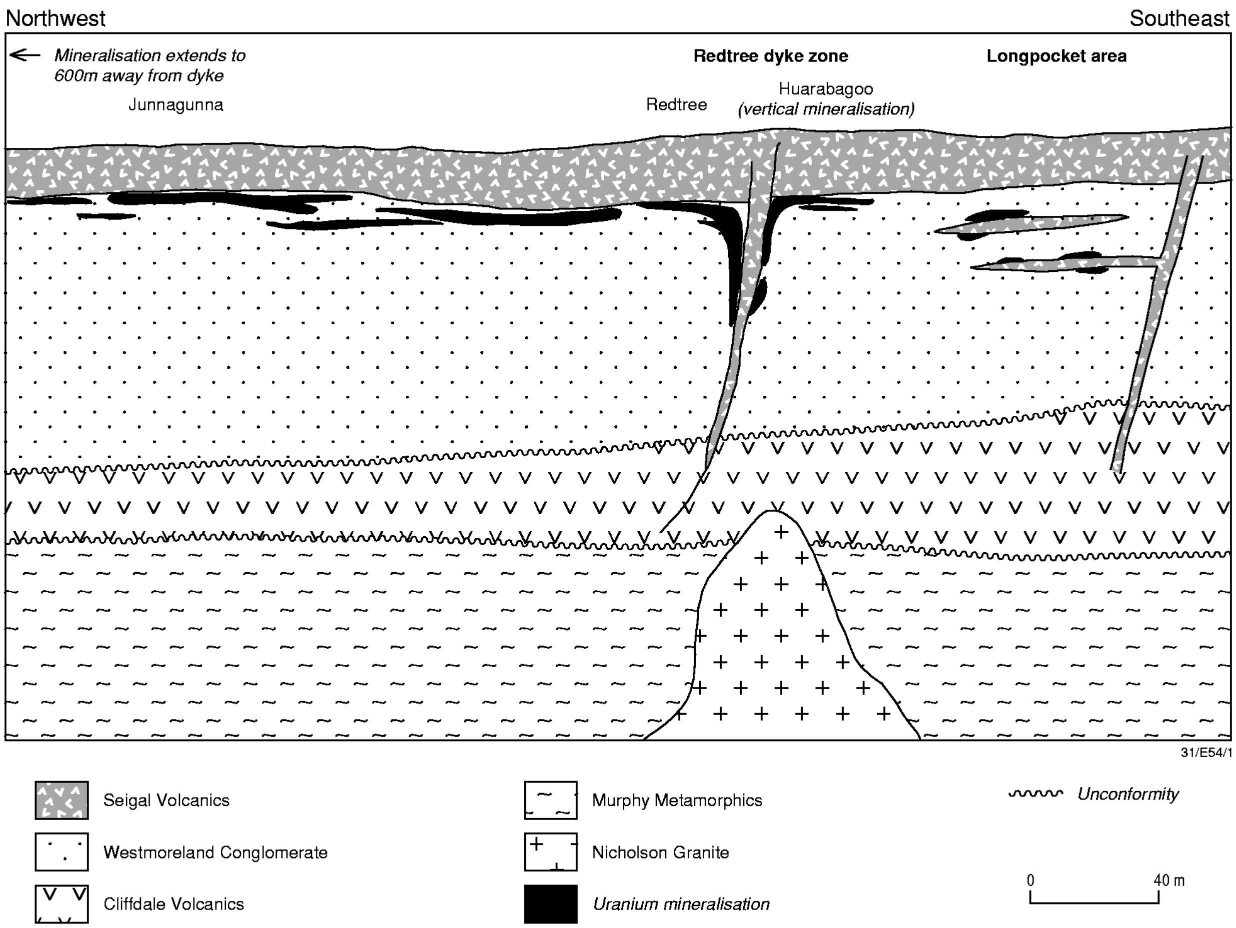

Figure 34. Diagrammatic cross-section of uranium deposits in the Westmoreland area (after Fuchs & Schindlmayr, 1981)

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.

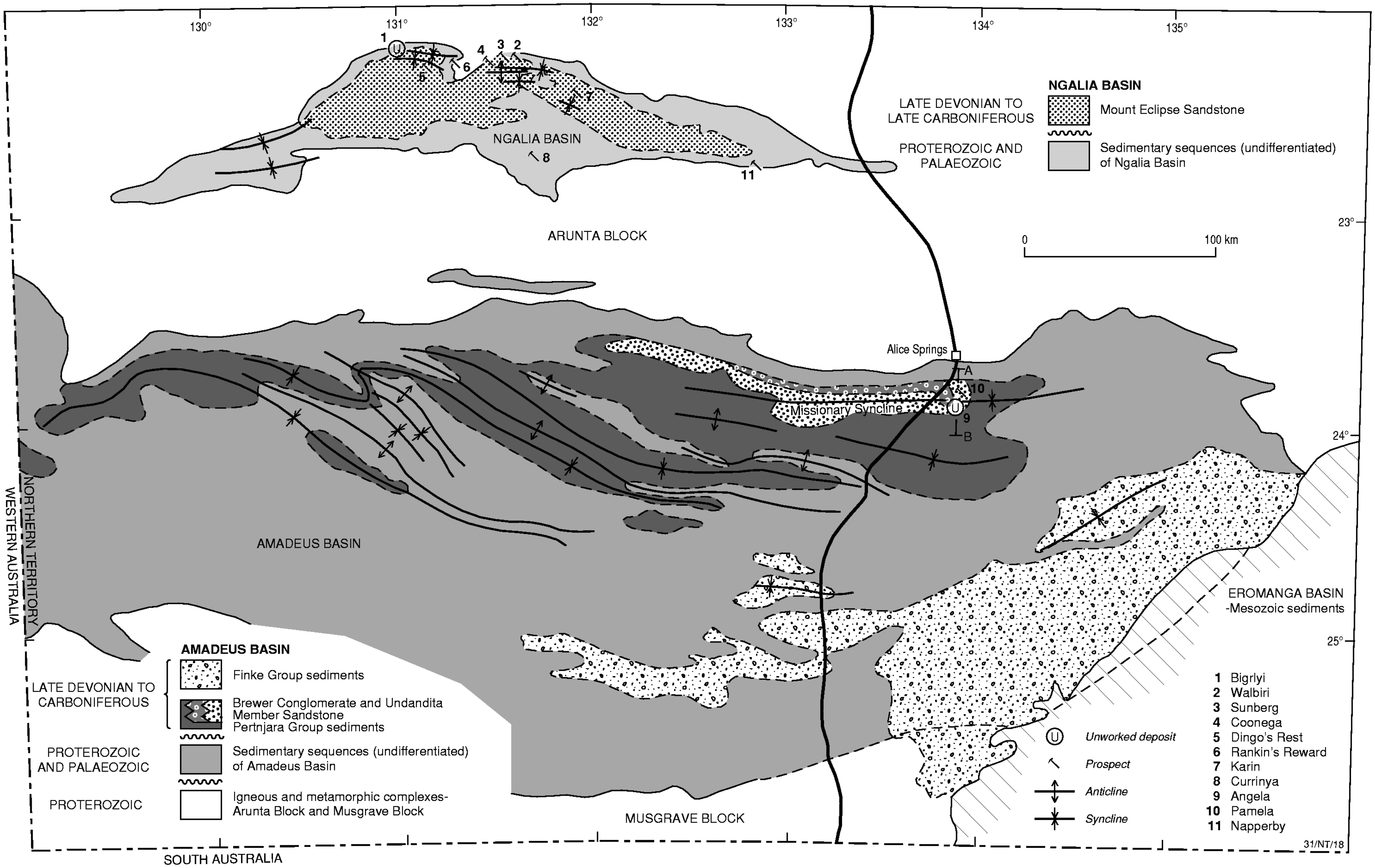

Figure 35. Simplified geology of the Ngalia and Amadeus Basins (NT), showing the Mount Eclipse Sandstone, Pertnjara Group, Finke Group and principal uranium deposits and prospects

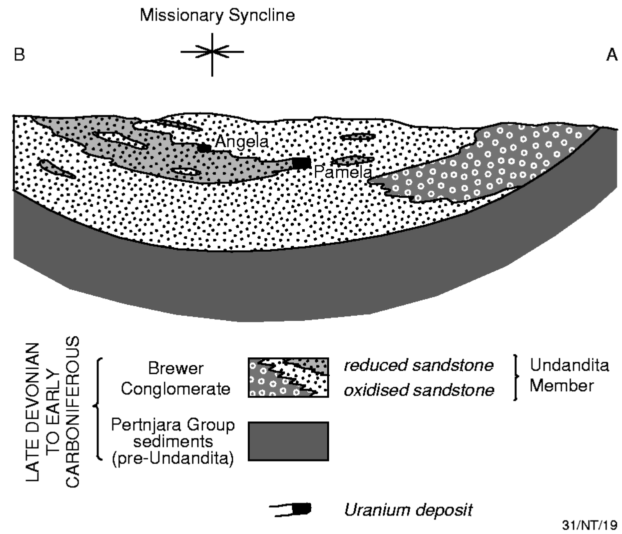

Figure 36. Diagrammatic cross-section of Missionary Syncline showing Angela and Pamela deposits (after Borschoff & Faris, 1990) along line A–B marked on Figure 35

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):

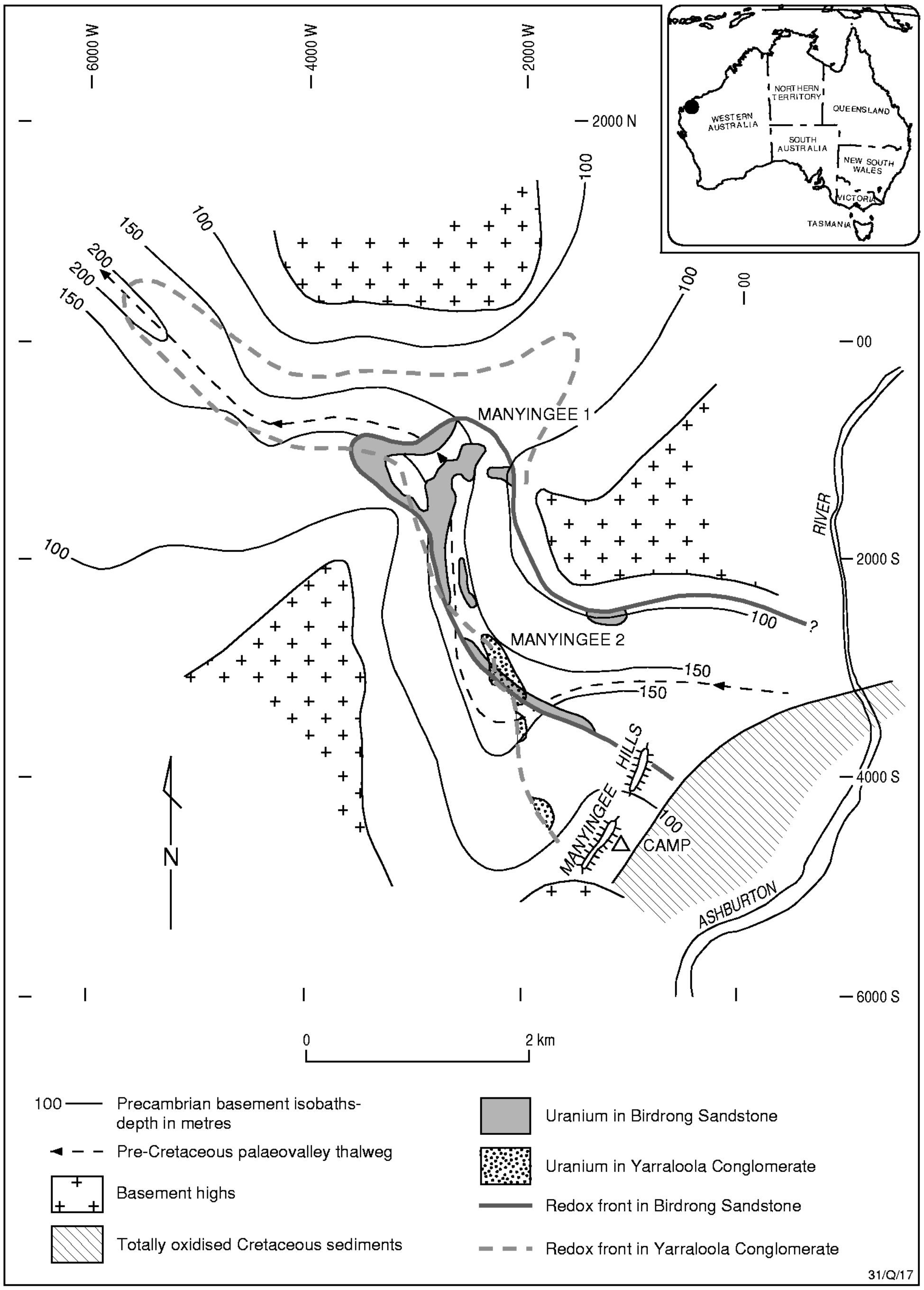

Figure 37. Geological plan of Manyingee deposit (after Bautin & Hallenstein, 1997)

- 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

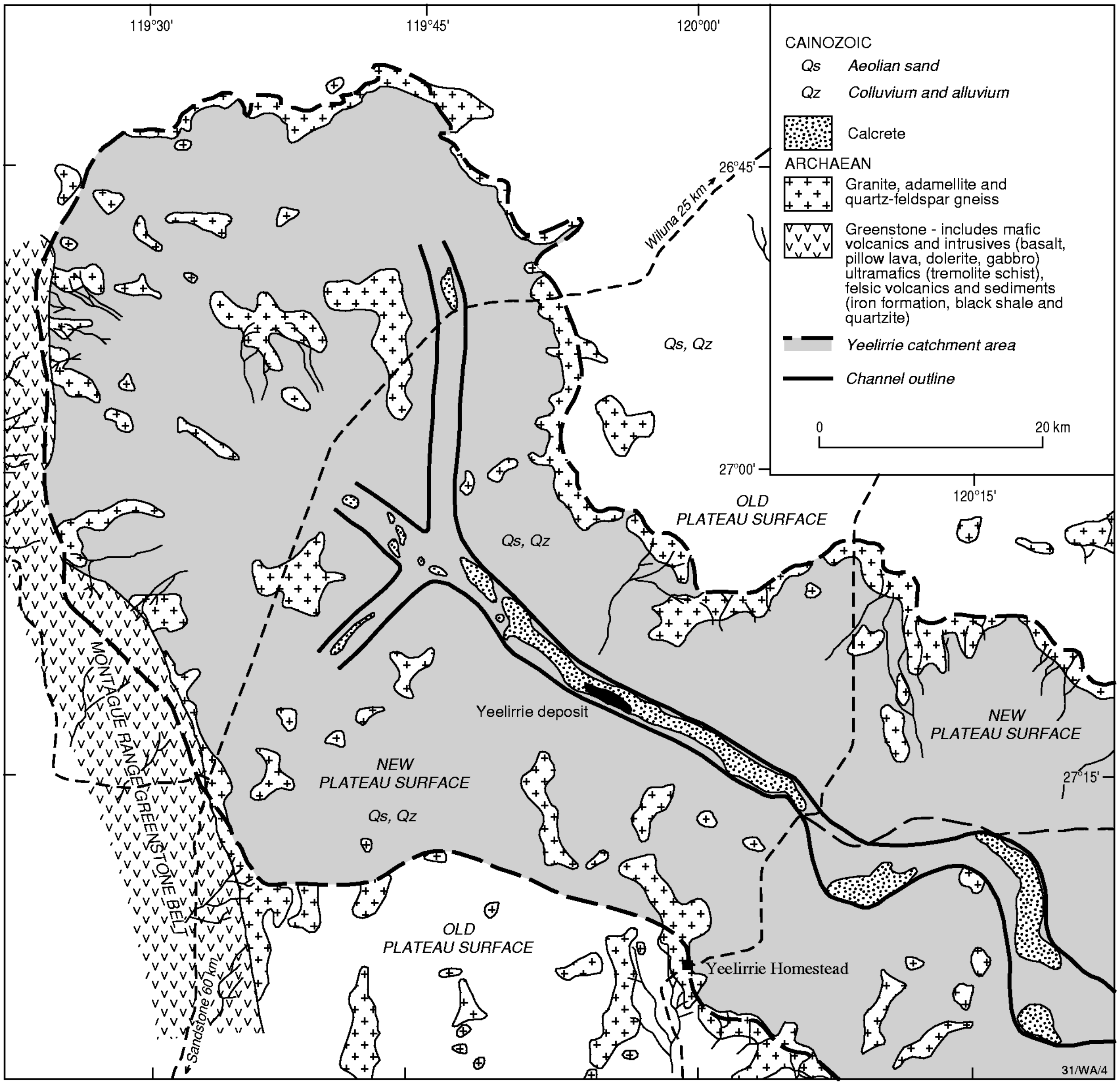

Figure 38. Regional geological setting of the Yeelirrie deposit (after Cameron, 1990)

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.

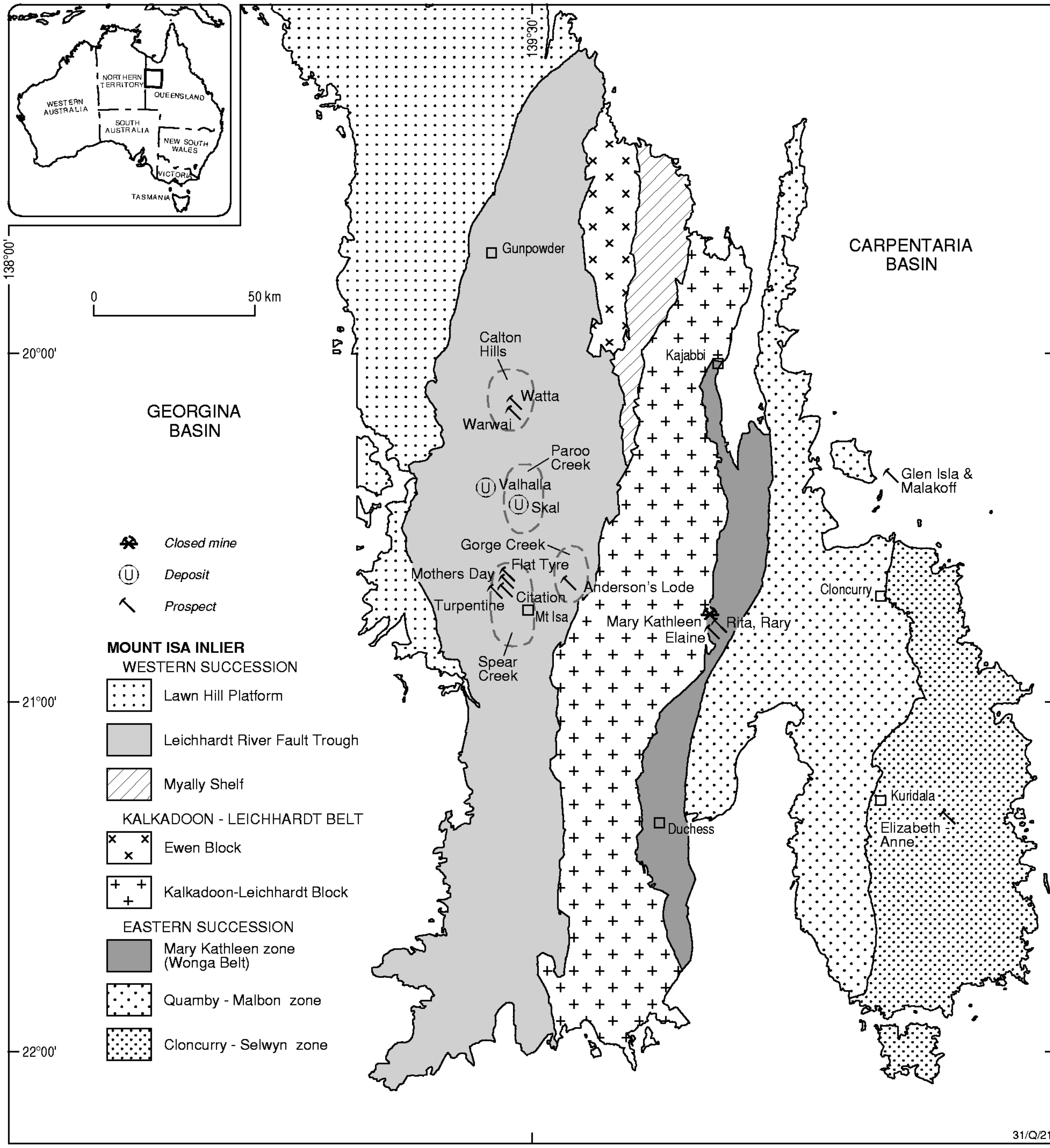

Figure 39. Regional geology of the Mount Isa Inlier and principal uranium deposits and prospects

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

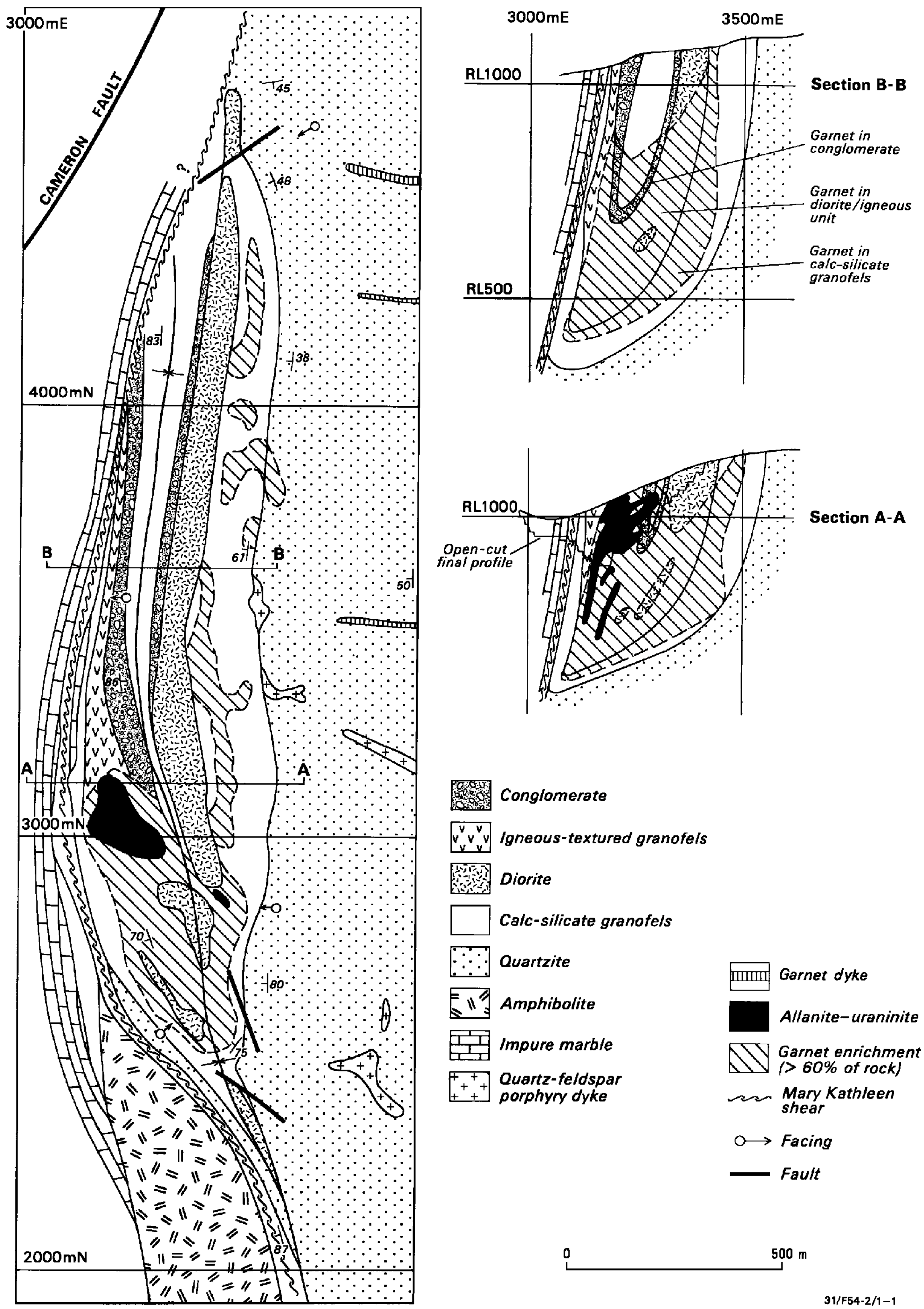

Figure 40. Geology of the Mary Kathleen deposit (after Scott & Scott, 1985)

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

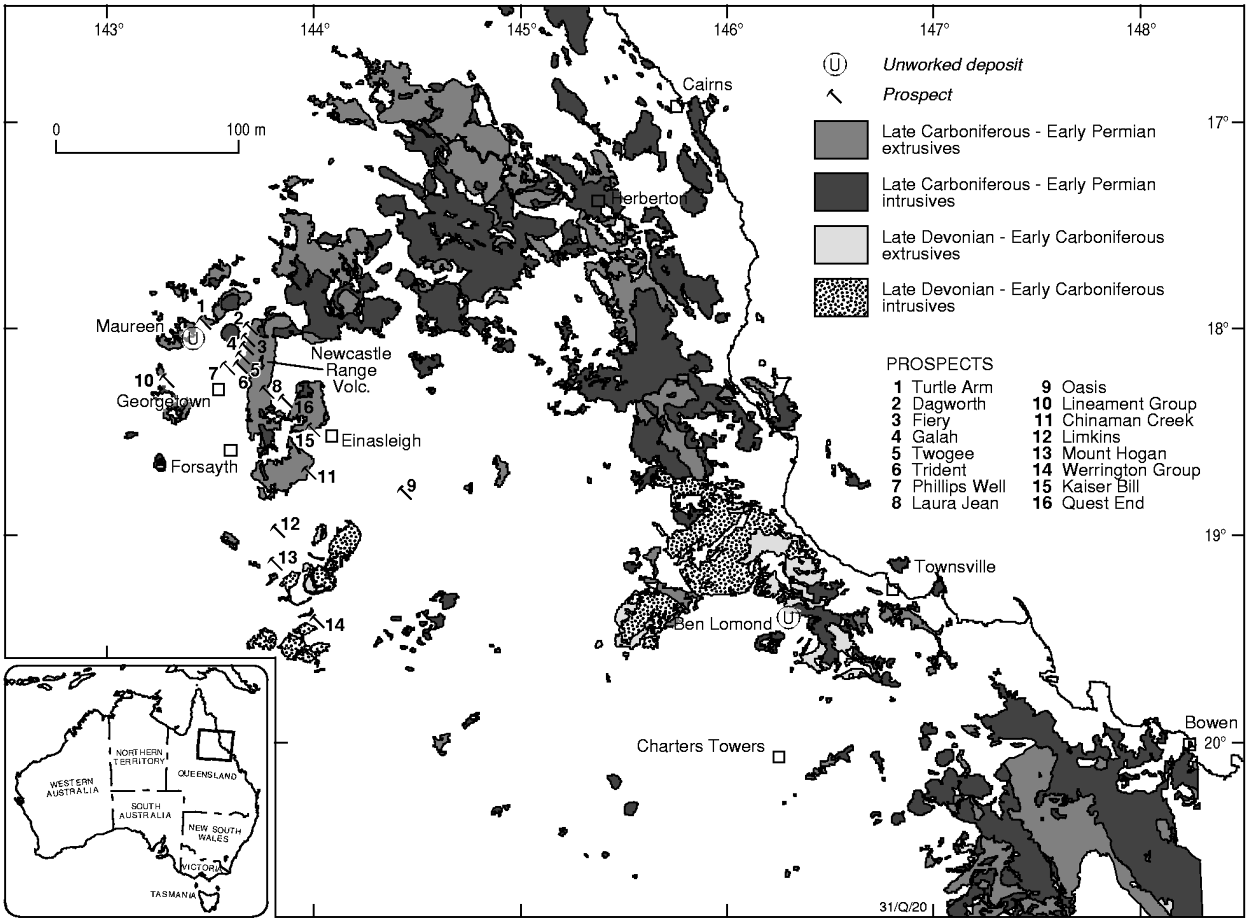

Figure 41. Granitoids, volcanics, and uranium deposits and prospects in the late Palaeozoic acid volcanic province, Georgetown–Townsville uranium field (after Bain & Draper, 1997a,b)

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

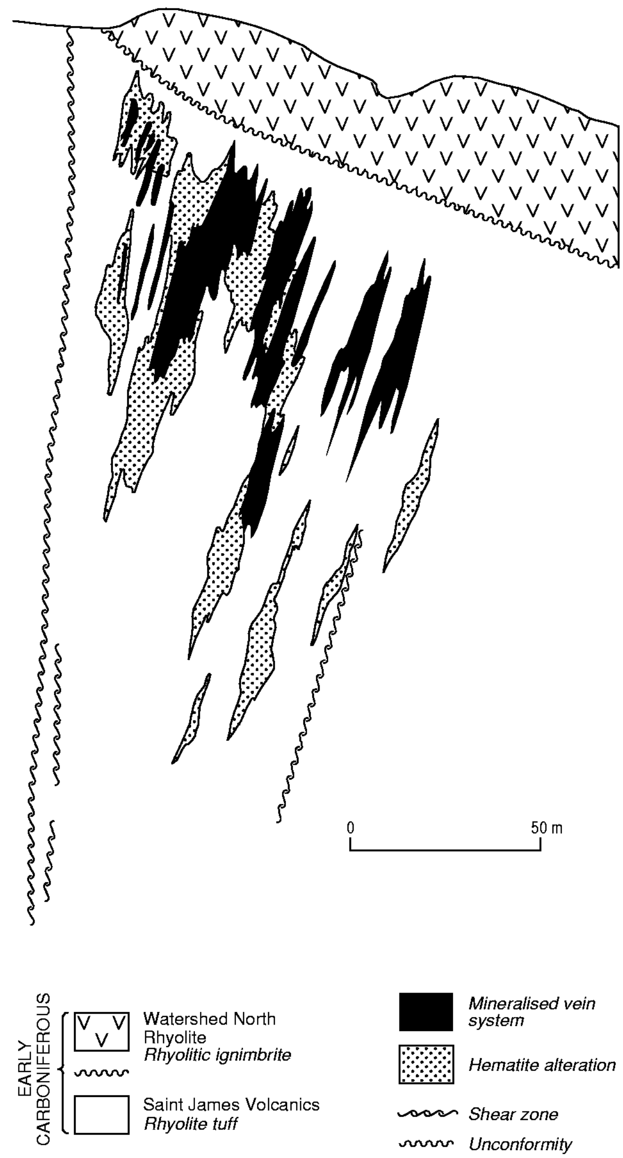

Figure 42. Cross-section, Ben Lomond deposit (after Minatome Australia Pty Ltd, 1983)

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;

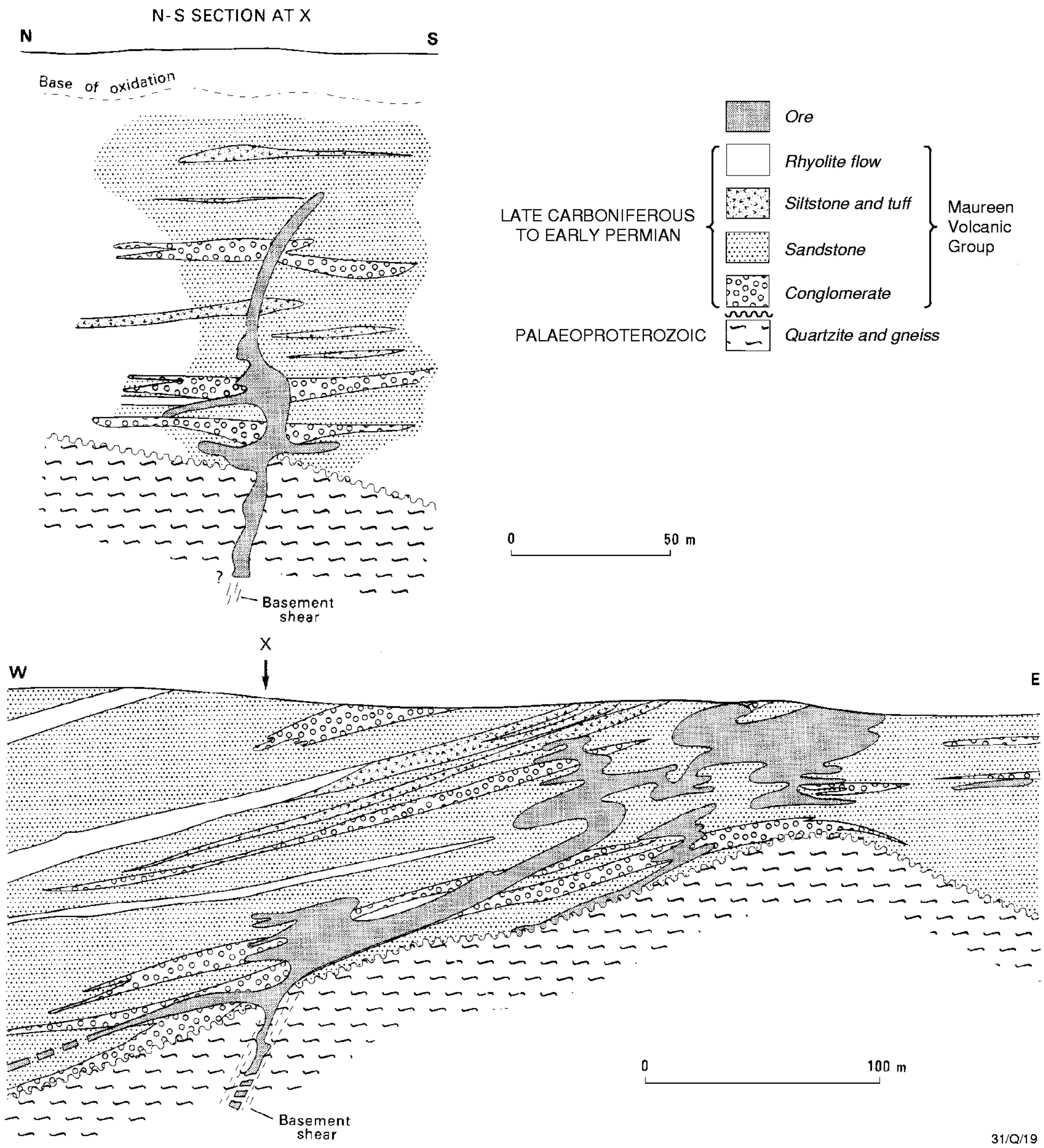

Figure 43. Cross-section and long-section of the Maureen deposit (after Bain & Withnall, 1980)

- *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.

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[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 %

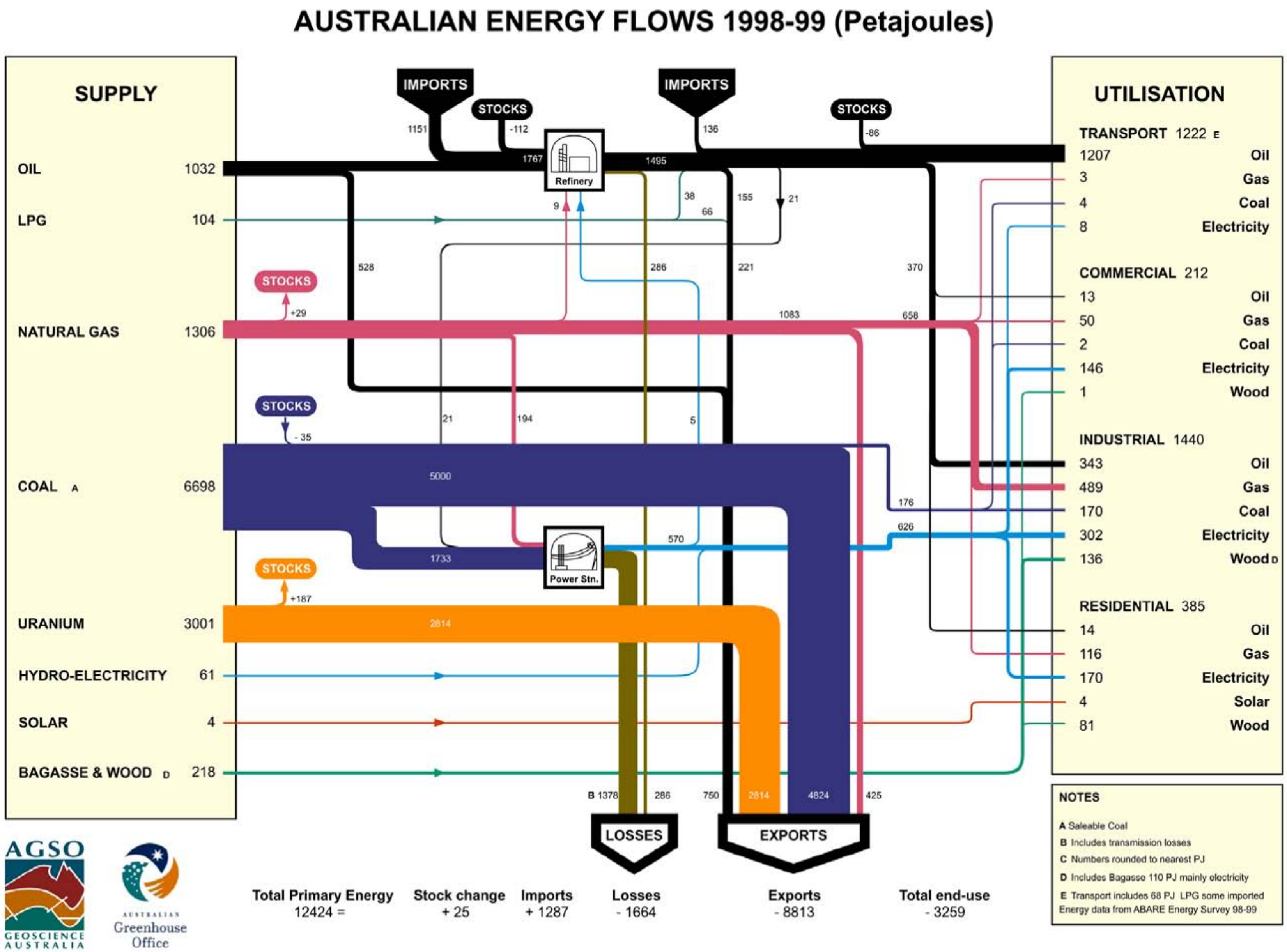

Figure 44. Australian energy flows 1998–99 (figure reproduced with permission of Australian Greenhouse Office, Commonwealth Department of Environment and Heritage)

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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