Australia's URANIUM resources, geology and development of deposits

A.D. McKay and Y. Miezitis

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AUSTRALIA'S URANIUM RESOURCES, GEOLOGY AND DEVELOPMENT OF DEPOSITS

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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.

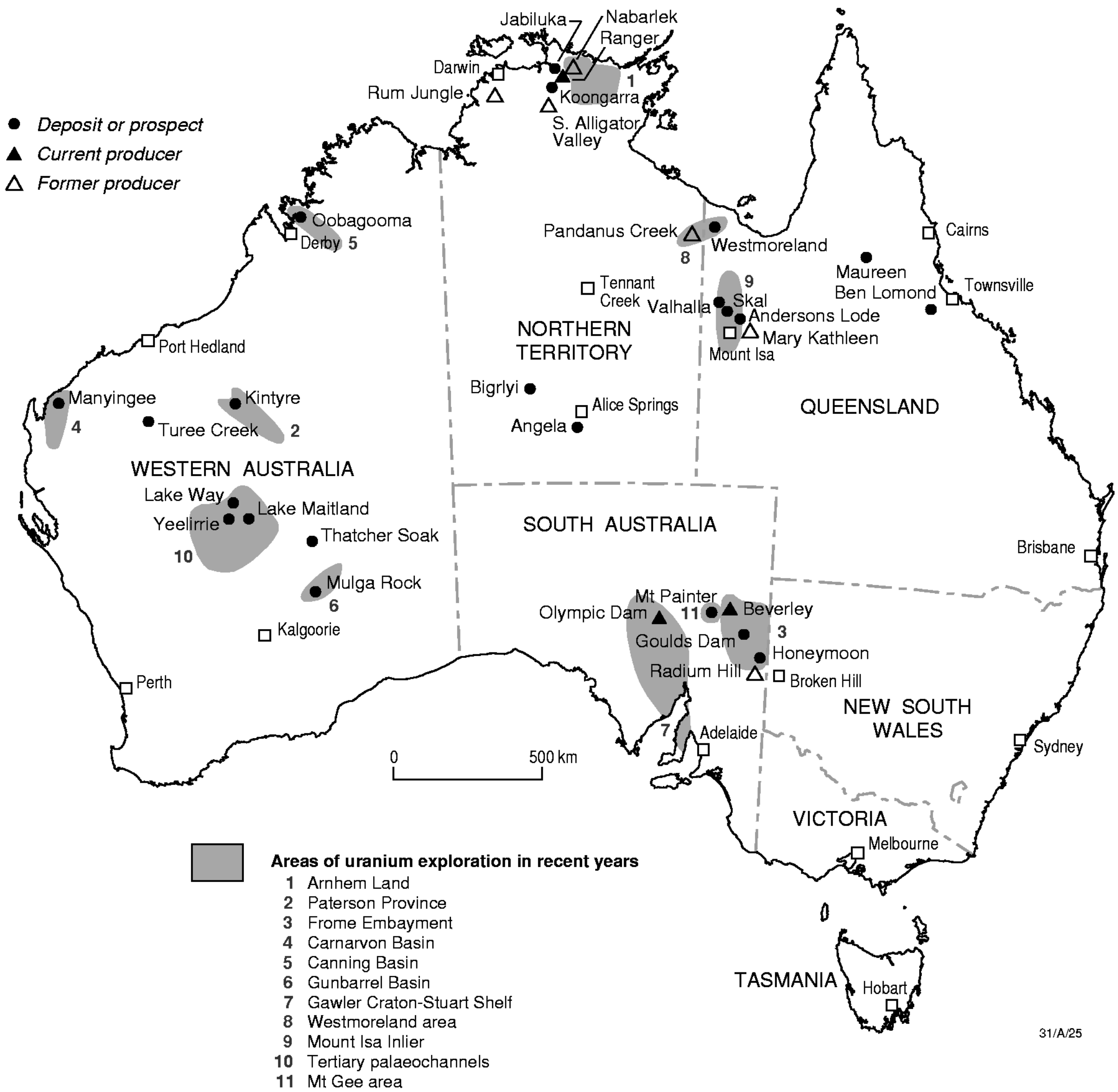

Figure 1. Australian uranium deposits and prospects, and areas of uranium exploration in recent years

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.

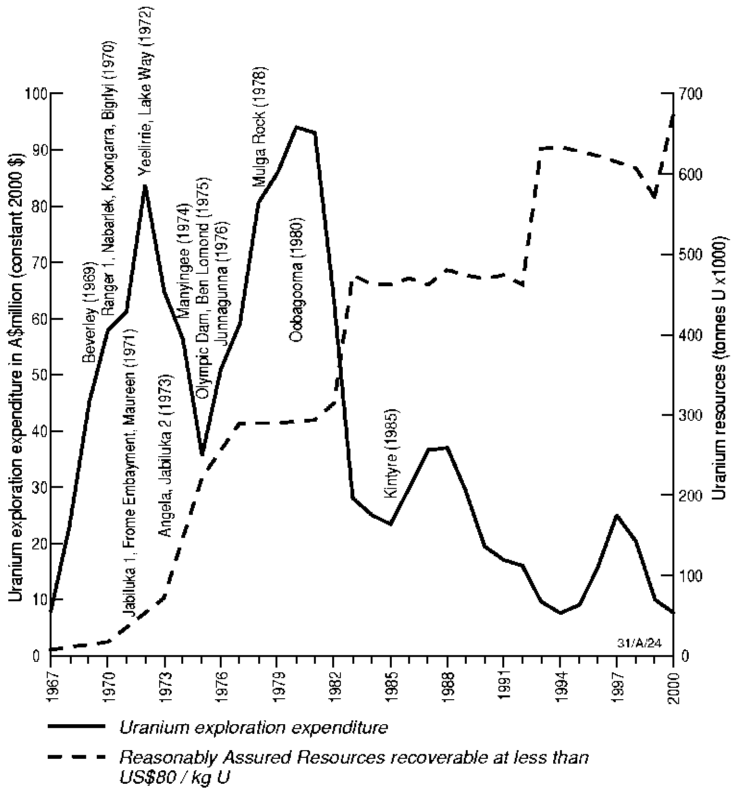

Figure 2. Comparison between annual expenditures on uranium exploration and the discovery of deposits and growth in Australia's uranium resources

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 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).

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.

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.

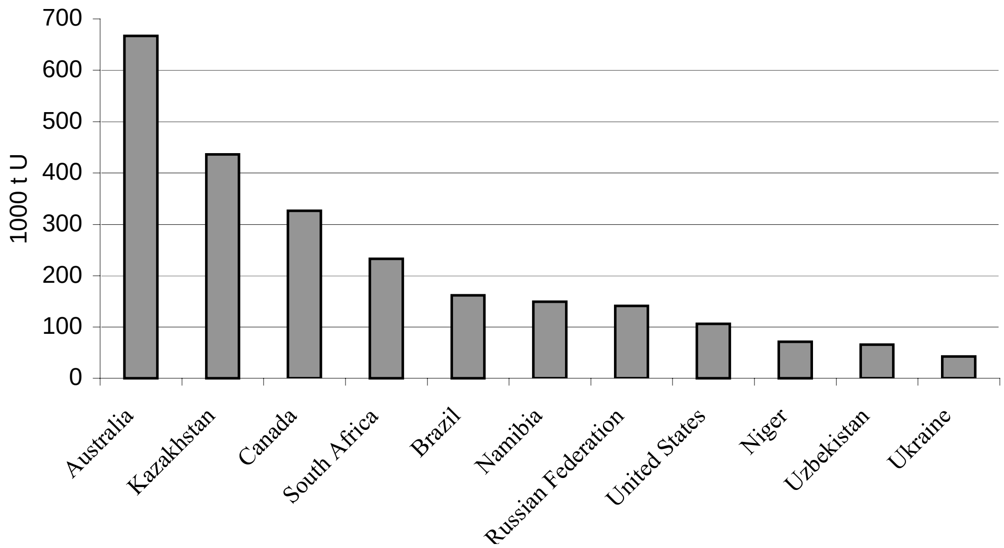

Figure 3. Reasonably Assured Resources of uranium recoverable at ≤US$80/kg U in major resource countries

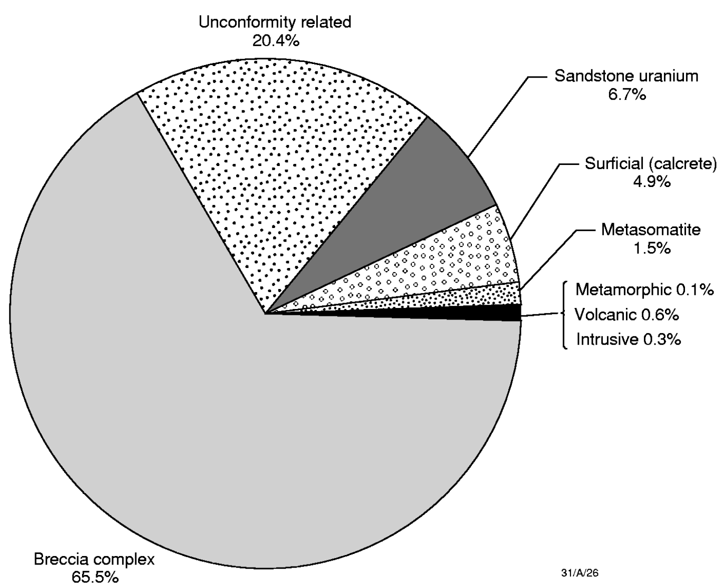

Figure 4. Distribution of Australia's uranium resources within deposit types

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

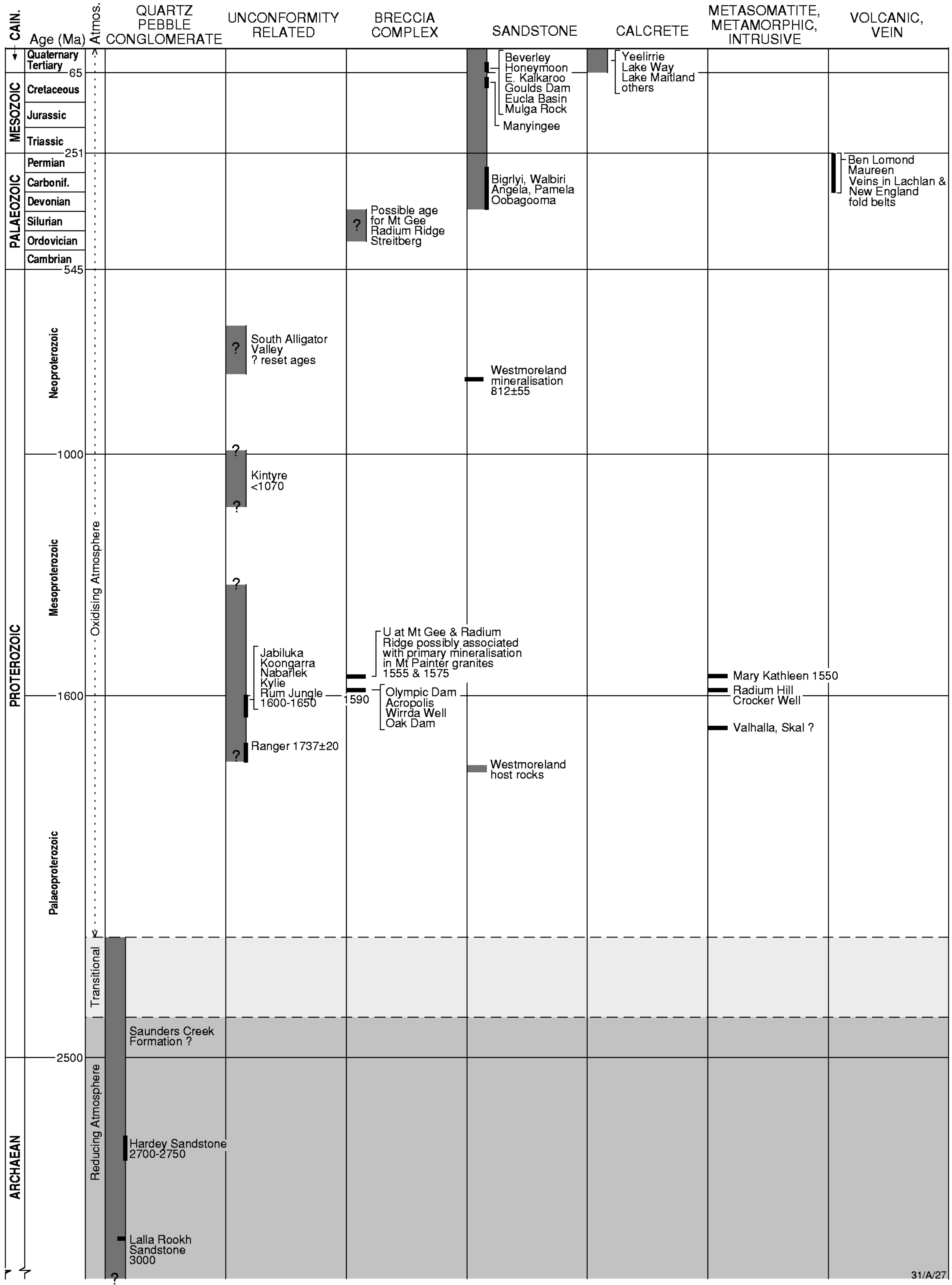

Figure 5. Ages of Australian uranium deposits, and age-ranges (vertical bars) of the major types of deposits worldwide. For sandstone-type deposits the ages shown are those of the host rocks; for the other deposits the ages include the oldest mineralisation, which is known at some deposits to have been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

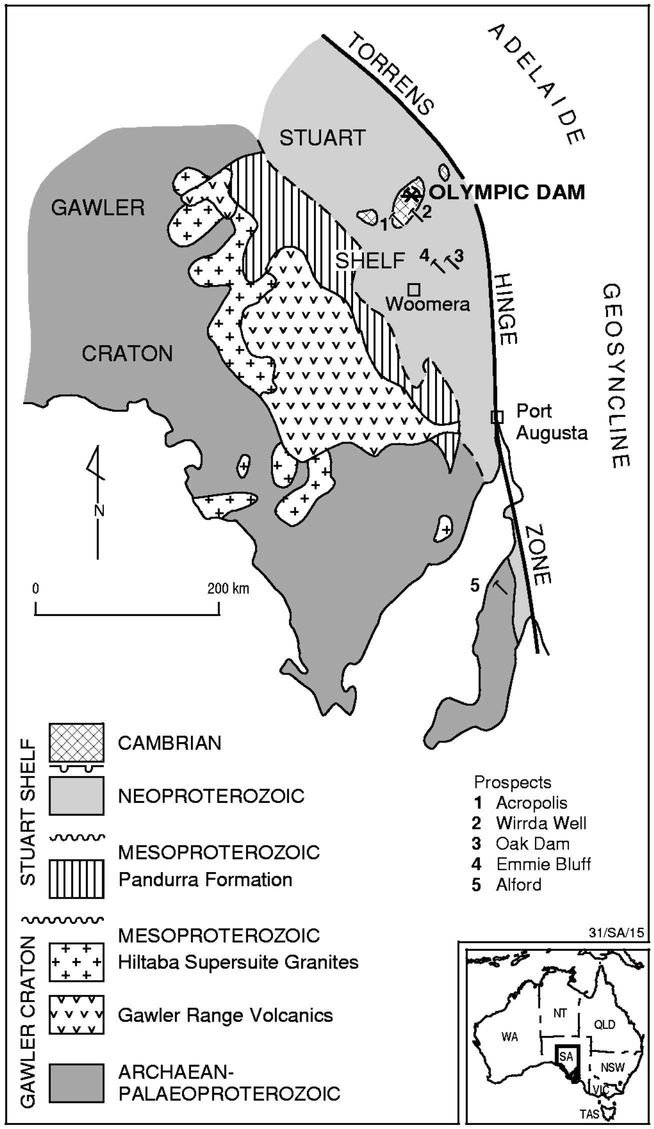

Figure 6. Location plan and simplified regional geology of the Gawler Craton and Stuart Shelf, South Australia (after Reeve & others, 1990)

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.

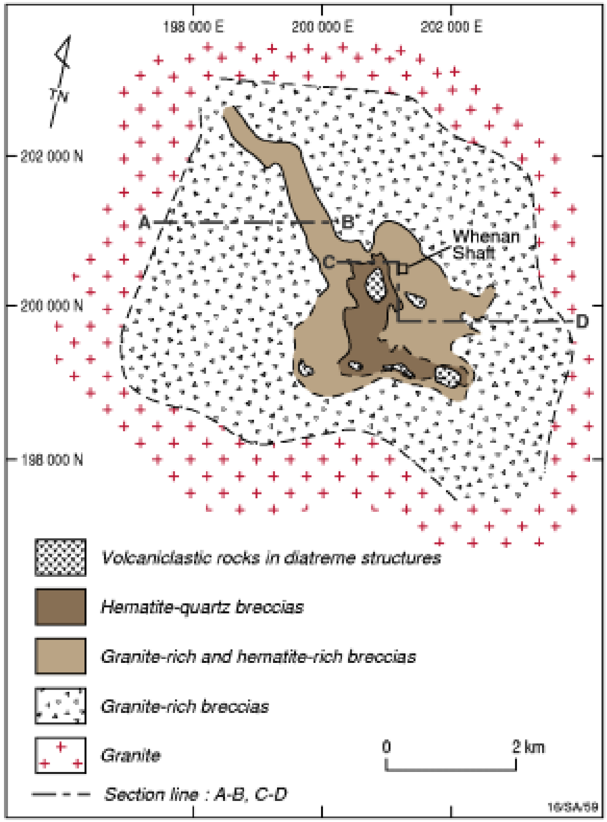

Figure 7. Simplified geological plan of the Olympic Dam Breccia Complex (modified after Reeve & others, 1990)

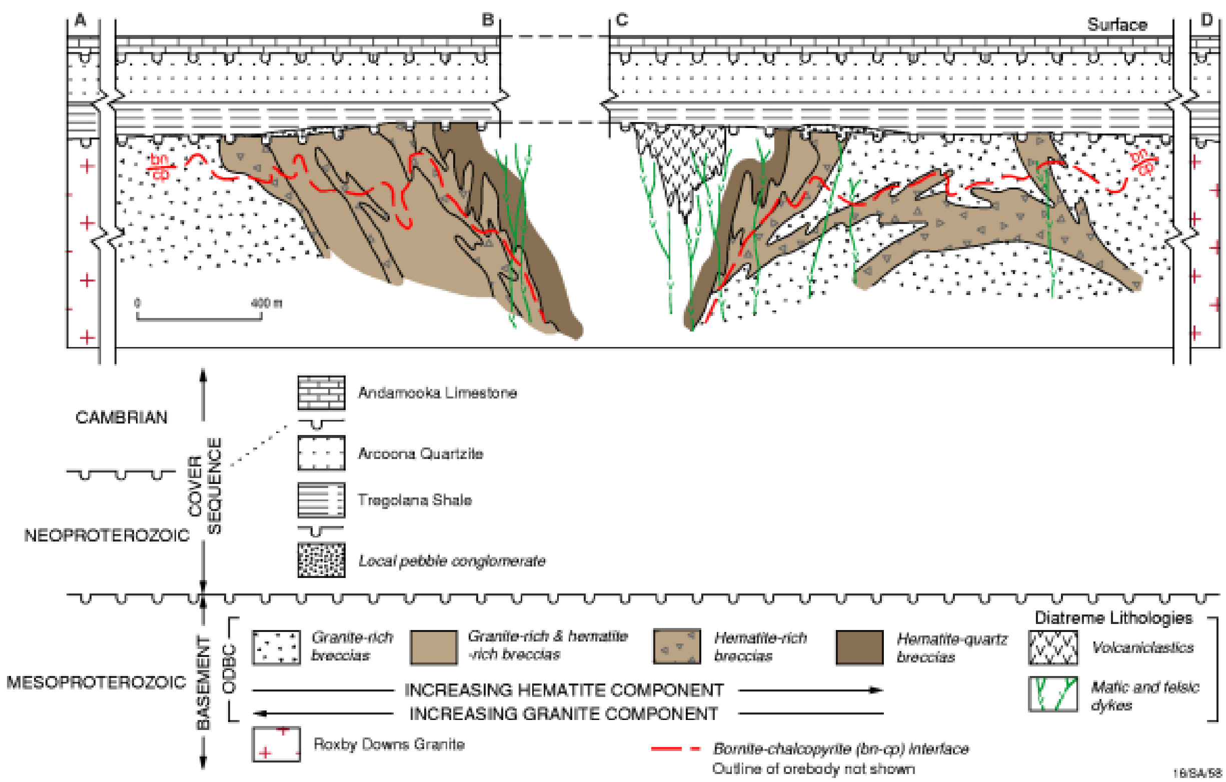

Figure 8. Simplified geological cross-section of the Olympic Dam Breccia Complex (modified after Reeve & others, 1990). Refer to Figure 7 for location of section A–B.

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

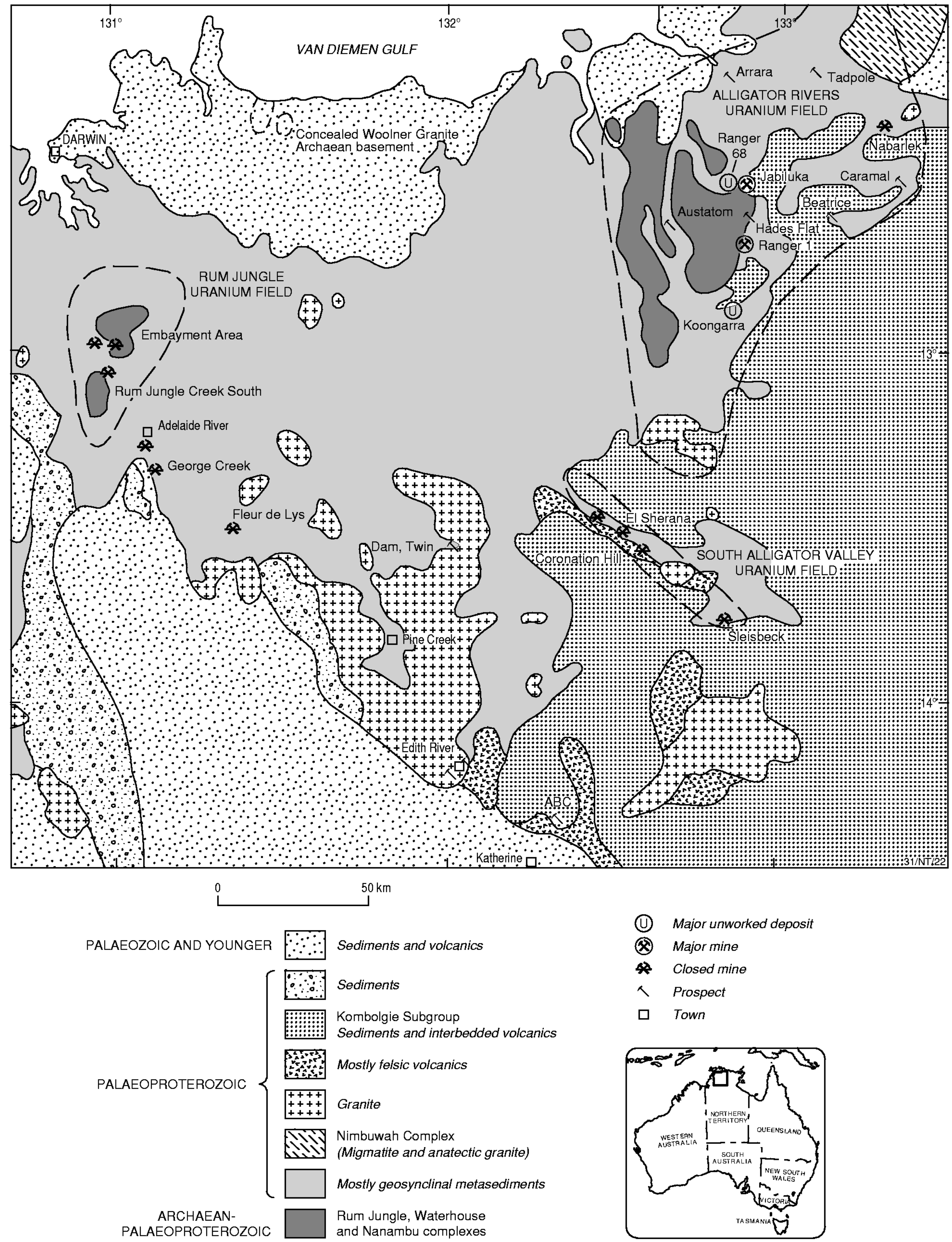

Figure 9. Generalised regional geology, Pine Creek Inlier, showing uranium fields, deposits and prospects

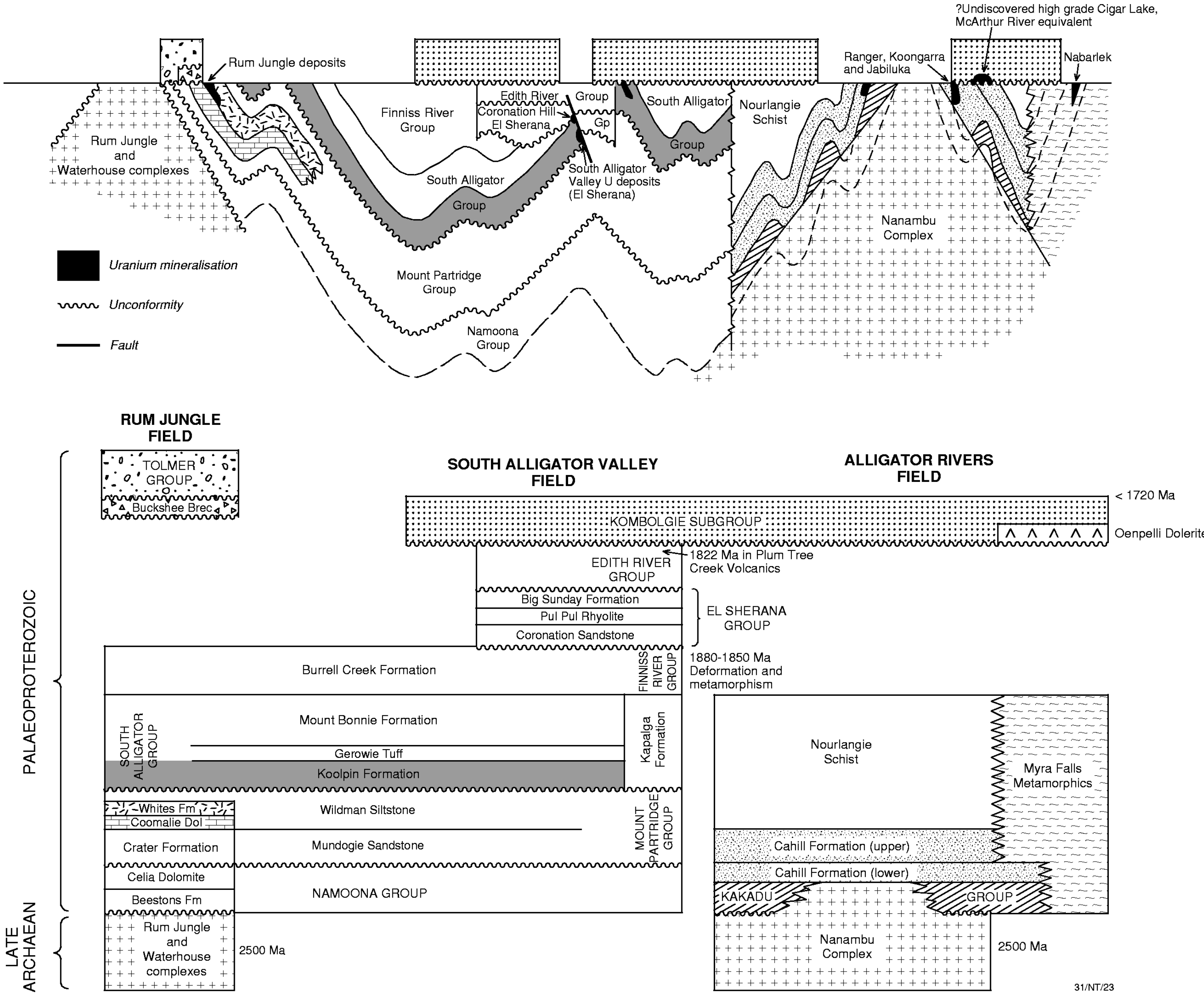

Figure 10. Schematic diagram of relationships between uranium mineralisation, favourable host rocks and Palaeoproterozoic unconformity in the Pine Creek Inlier. The diagram does not fully represent the stratigraphy, but shows the relationships between units significant in describing the uranium mineralisation.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

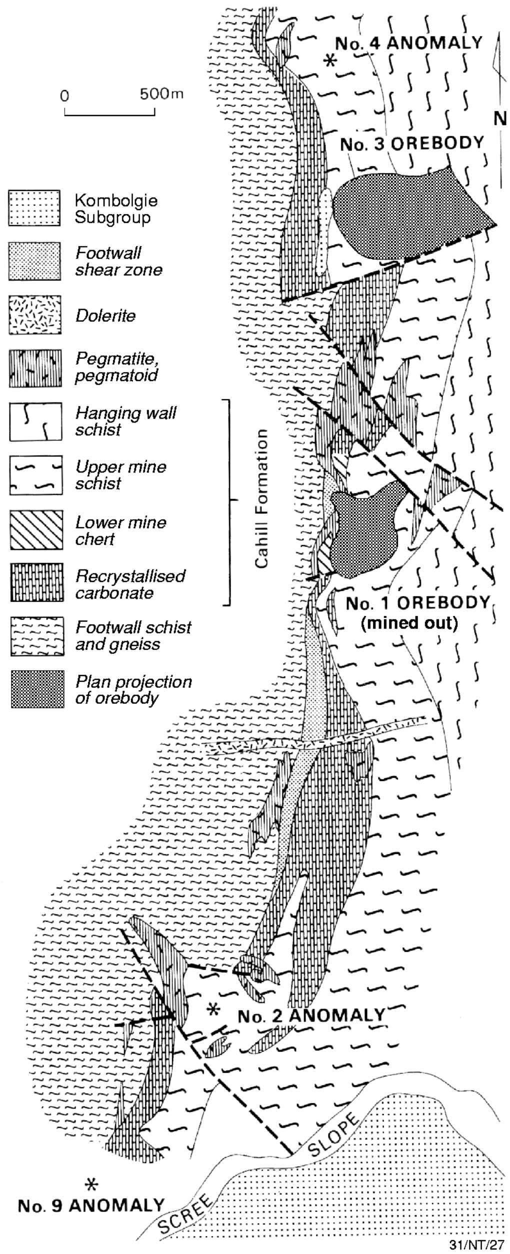

Figure 11. Generalised geological plan of Ranger 1 orebodies and prospects (from Needham, 1982a, after Eupene & others, 1975, and Hegge & others, 1980)

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%

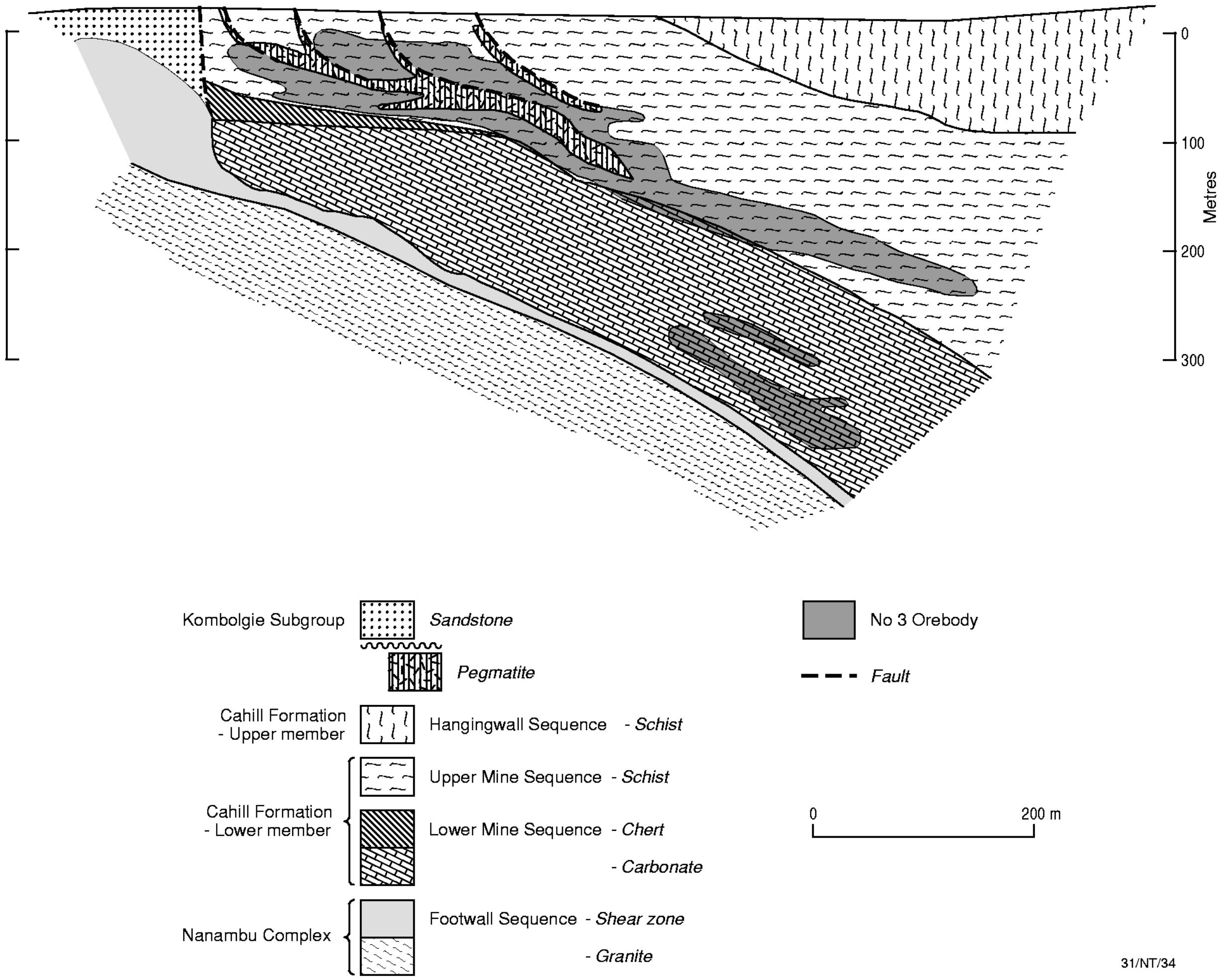

Figure 12. Schematic E–W cross-section, Ranger 1 No. 3 Orebody (L Hughes, Energy Resources of Australia Pty Ltd, December 1999)

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.

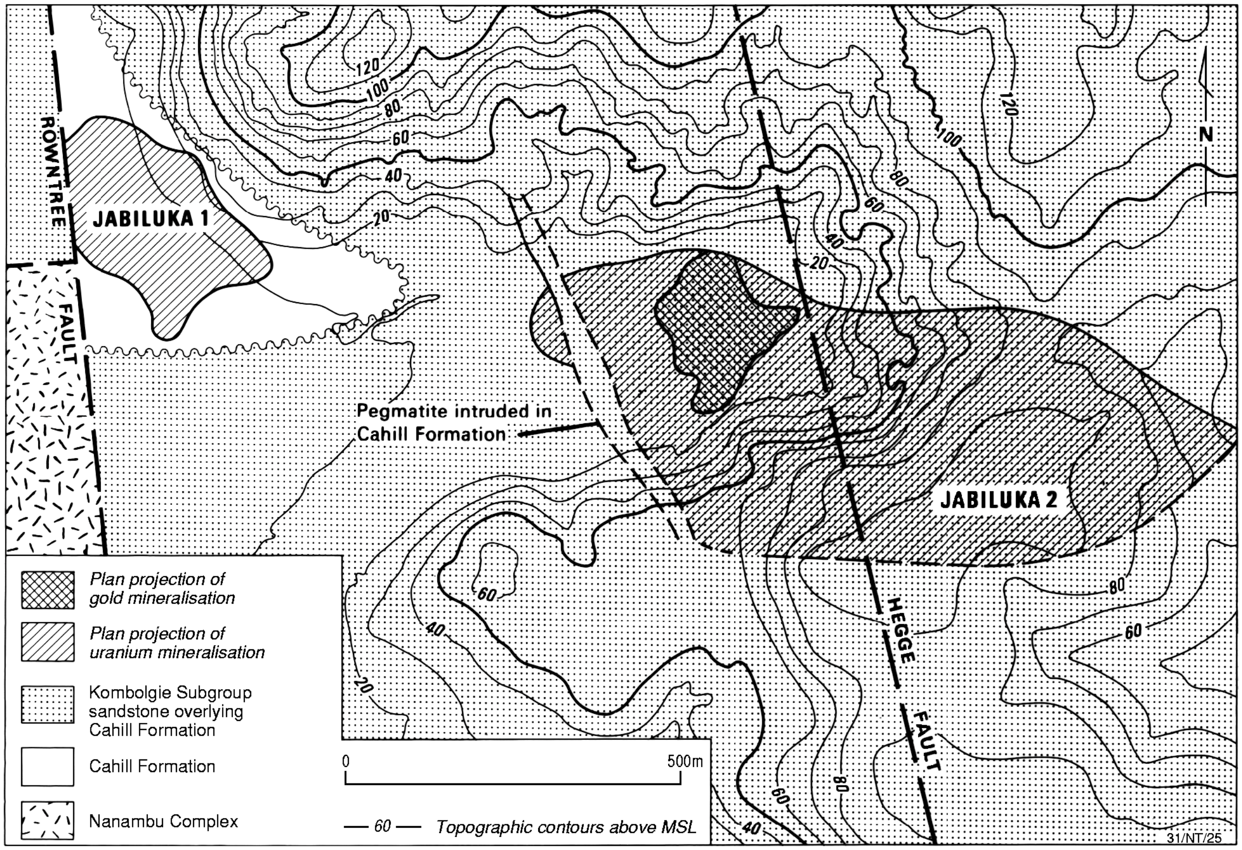

Figure 13. Geological plan of Jabiluka 1 and 2 deposits (after Needham, 1982a, adapted from revised unpublished data by Pancontinental Mining Ltd)

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.

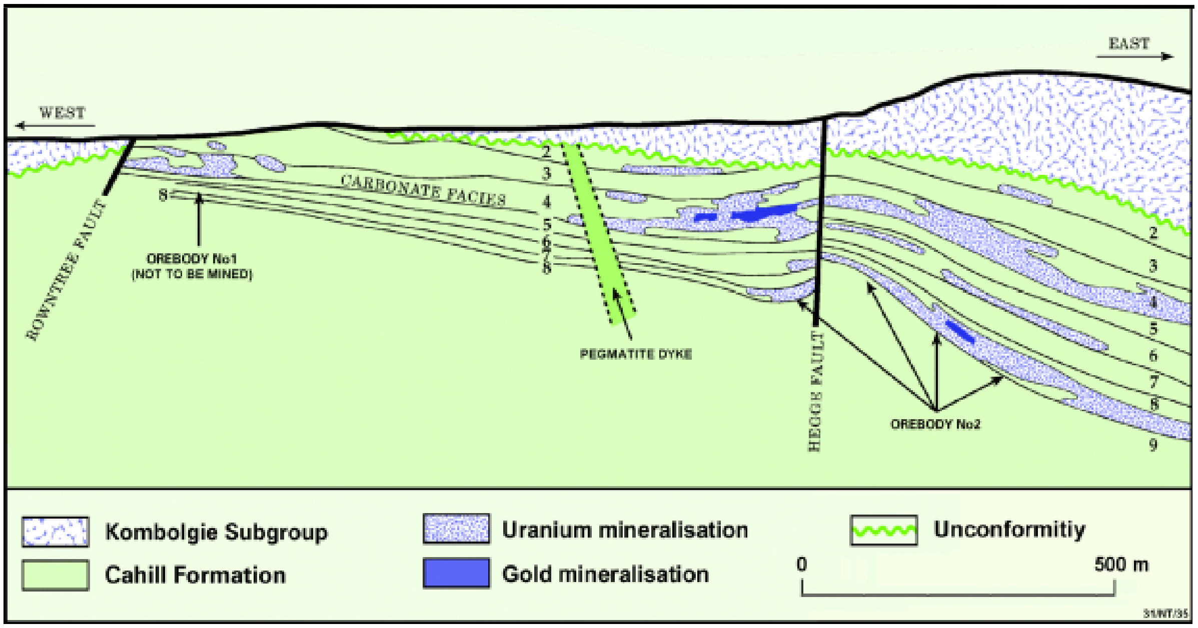

Figure 14. Generalised long-section of Jabiluka 1 and 2 deposits (Kinhill, 1996)

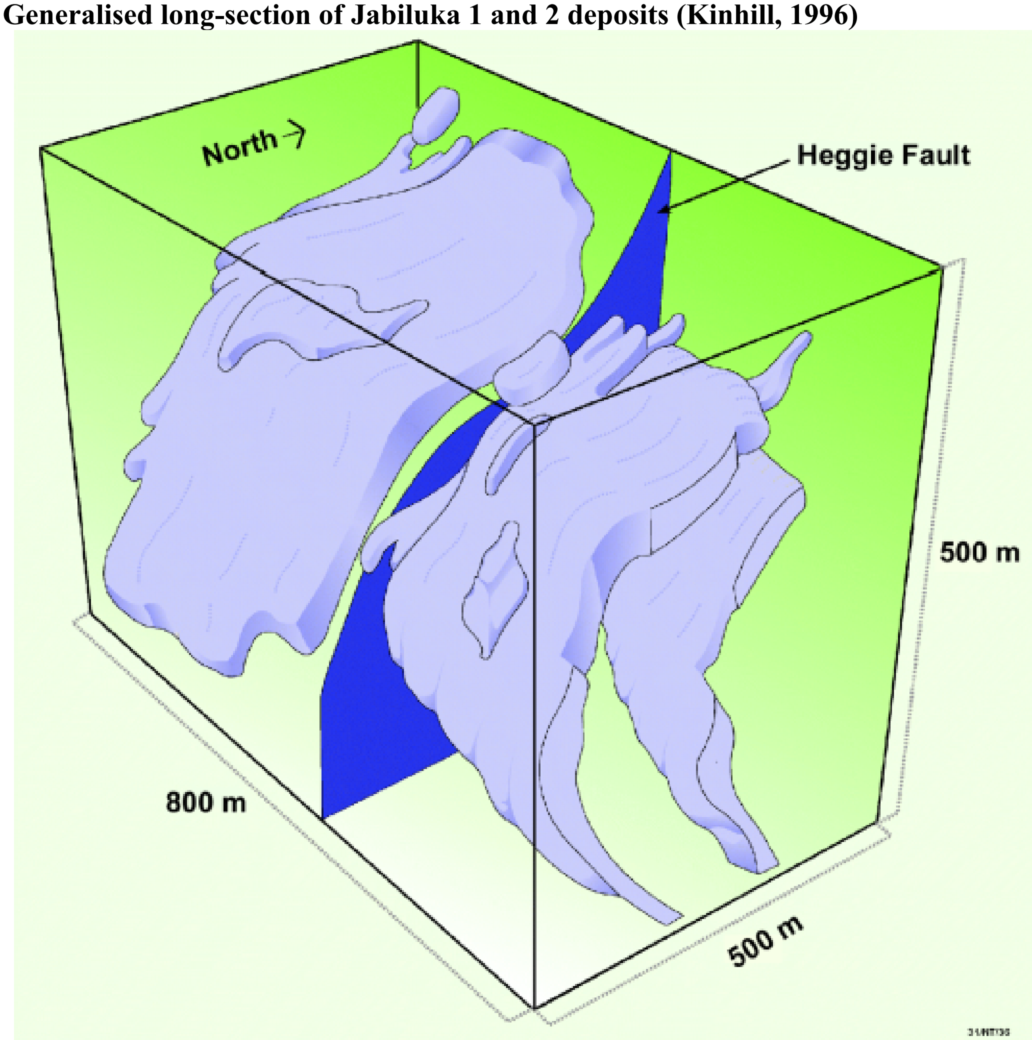

Figure 15. Jabiluka 2 deposit, schematic perspective (Kinhill, 1996)

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.

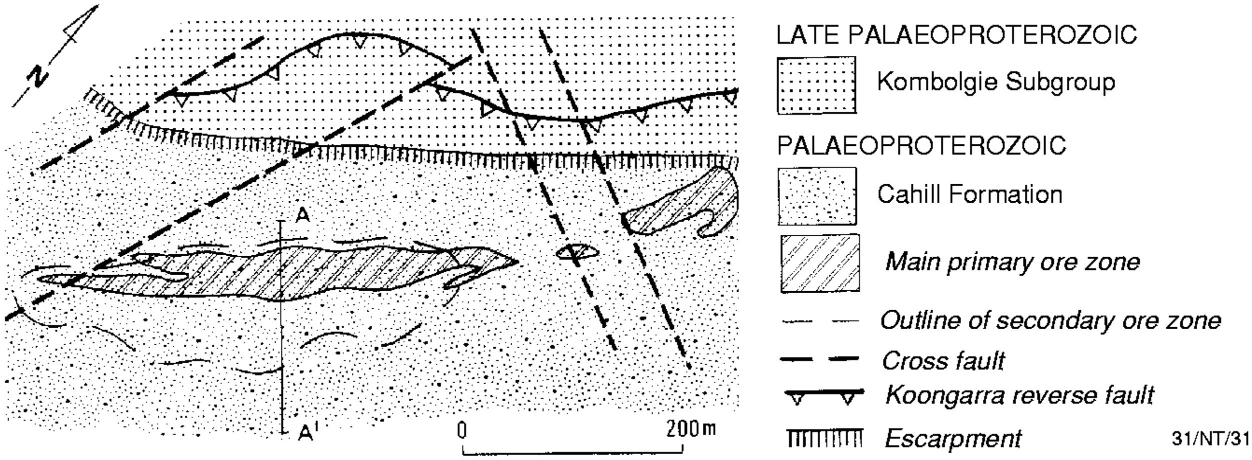

Figure 16. Plan of Koongarra orebodies (from Needham, 1982a, after Foy & Pedersen, 1975, and Hegge & others, 1980)

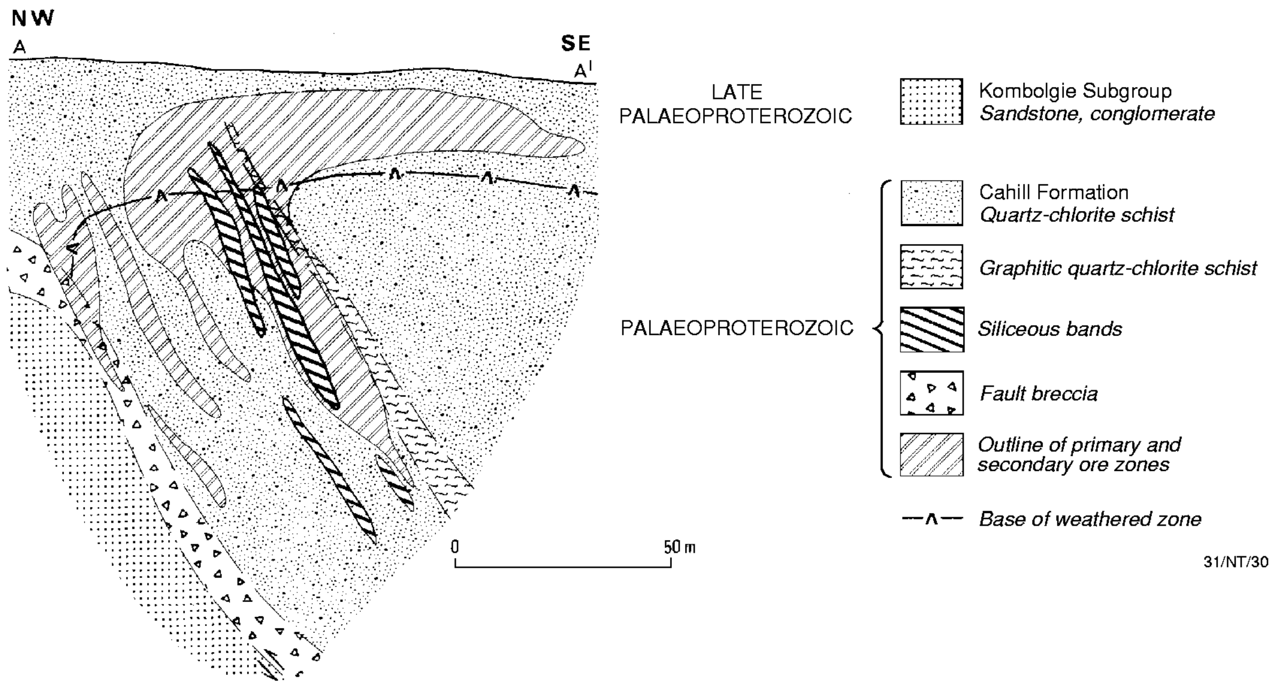

Figure 17. Cross-section, Koongarra No. 1 Orebody (from Needham, 1982a, after Foy & Pedersen, 1975, and Hegge & others, 1980)

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).

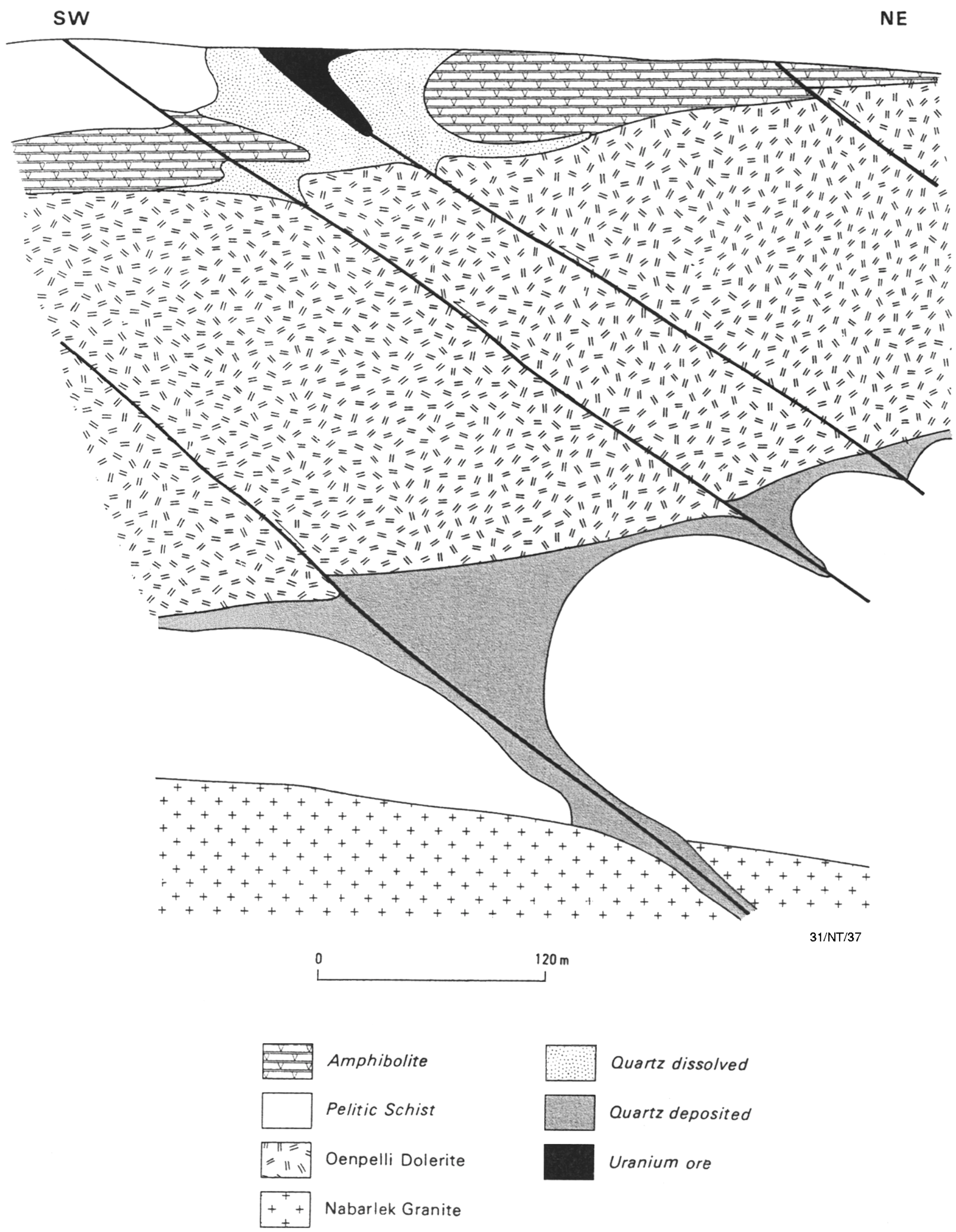

Figure 18. Geological cross-section 9700 m N through the Nabarlek deposit (from Wilde & Noakes, 1990)

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).

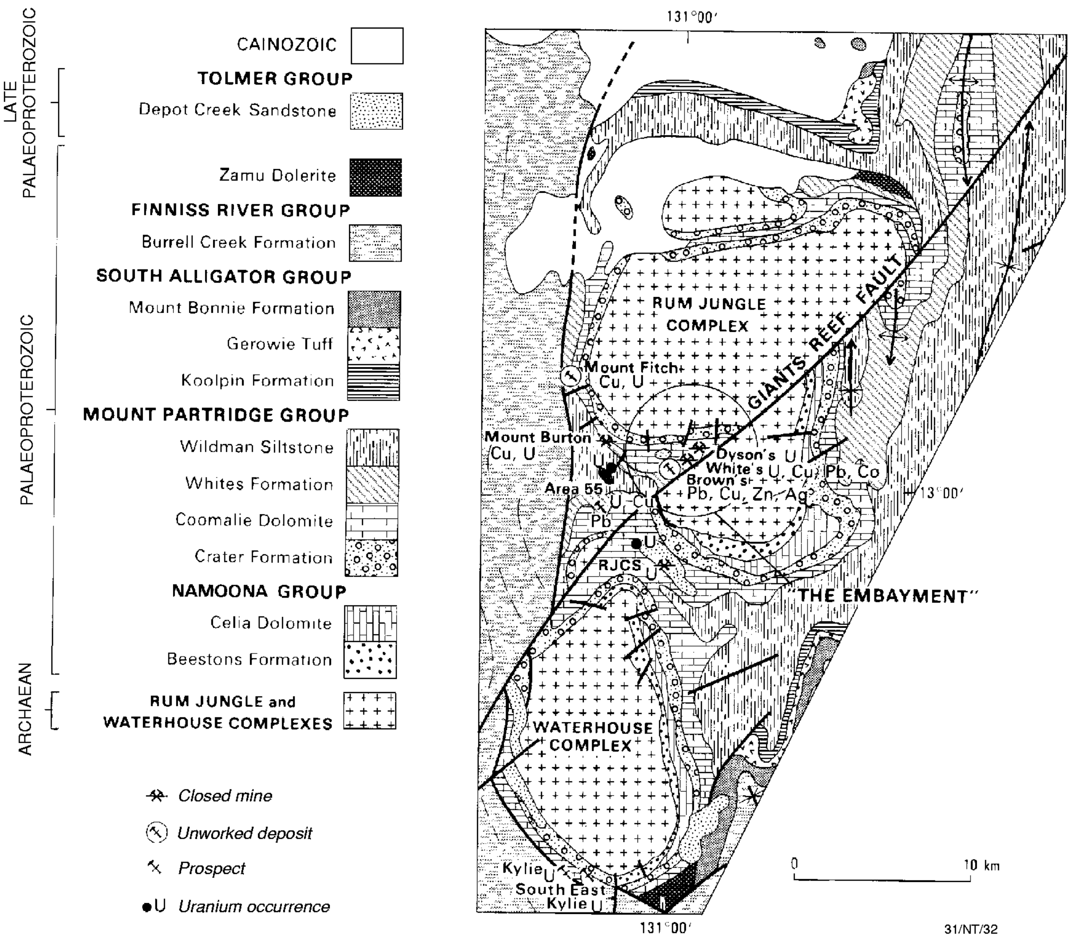

Figure 19. Geology of the Rum Jungle uranium field (modified after Ewers & others, 1984)

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.

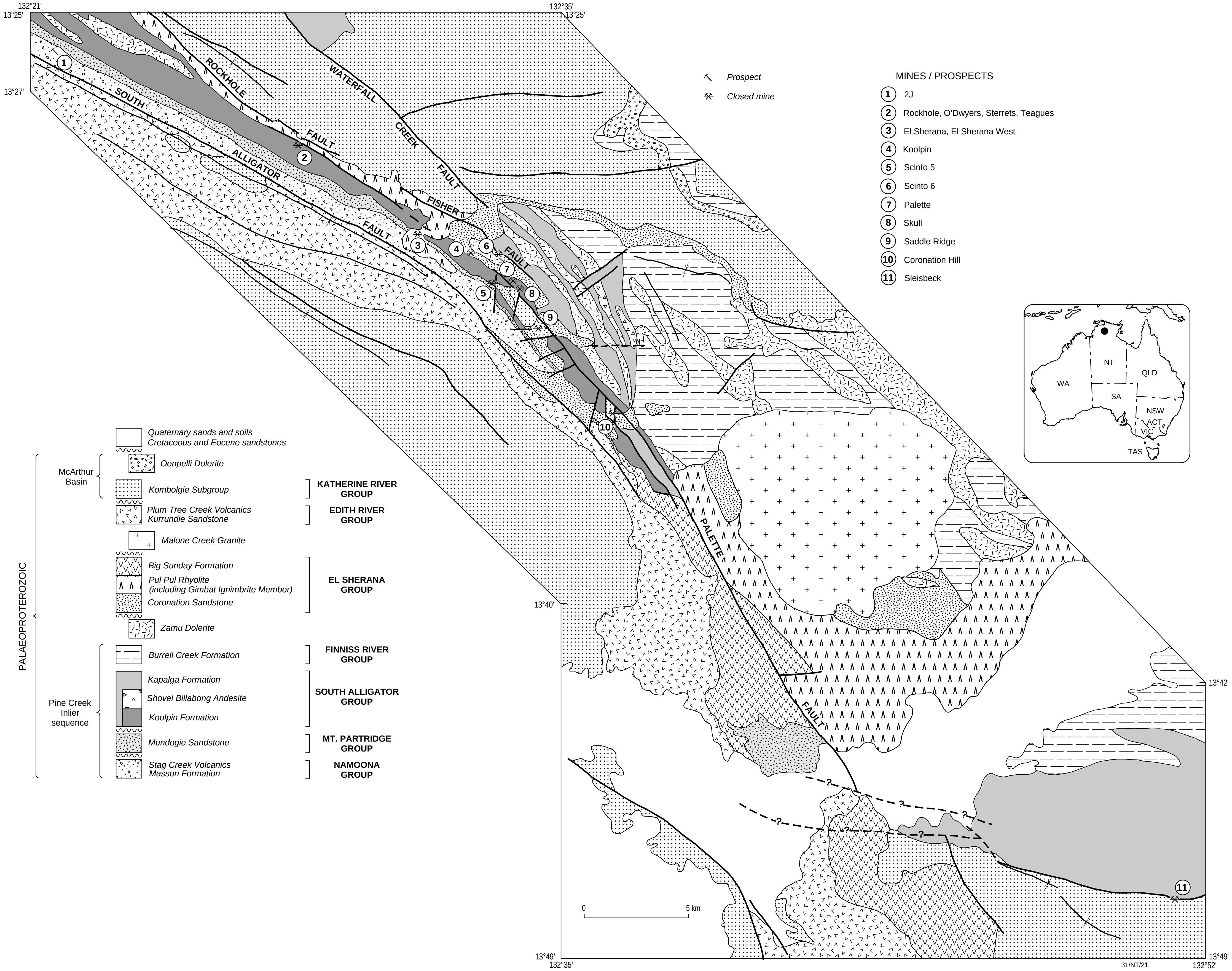

Figure 20. Simplified geology of the South Alligator Valley uranium field (compiled from maps in Needham, 1988a; Friedmann & Grotzinger, 1991; Valenta, 1991; Jagodzinski, 1999)

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.

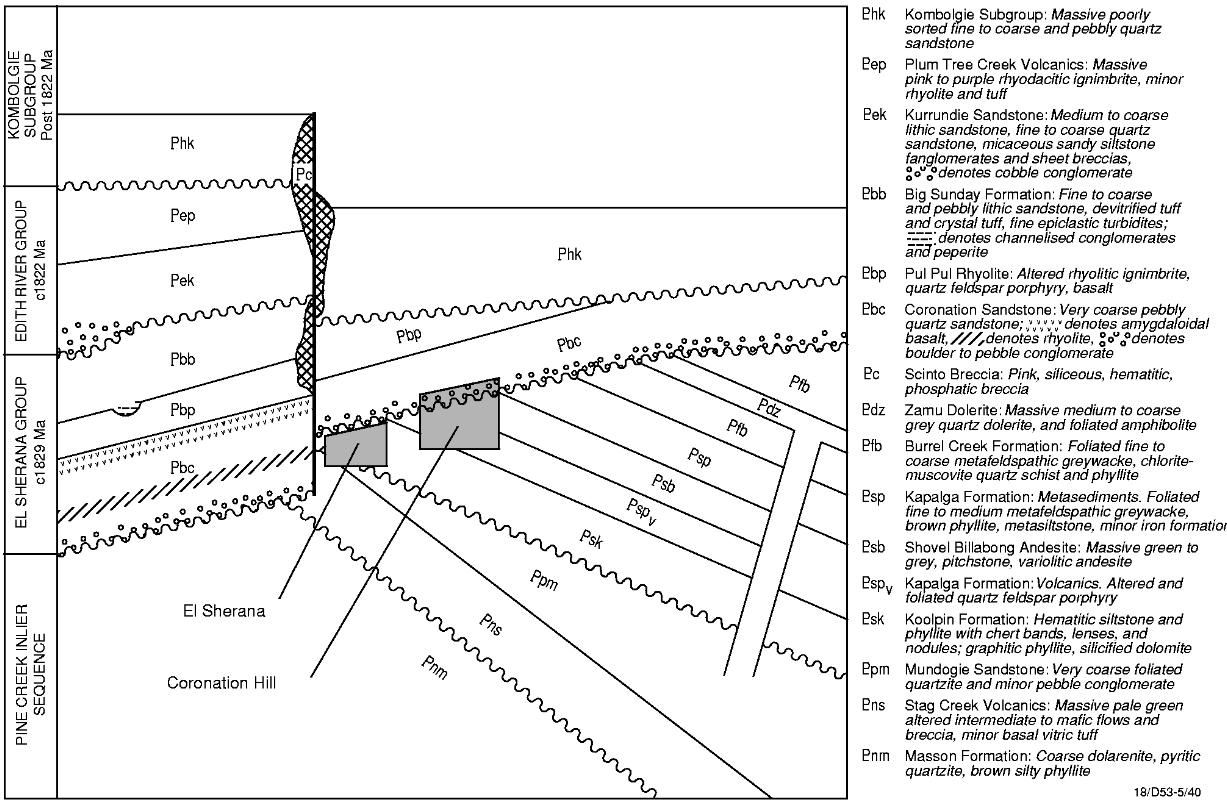

Figure 21. Schematic relationship of the El Sherana and Coronation Hill deposits to the stratigraphic sequence in the South Alligator Valley (modified after Wyborn, 1992; age dates generalised after Jagodzinski, 1999; R.W. Page quoted in Kruse & others, 1994)

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

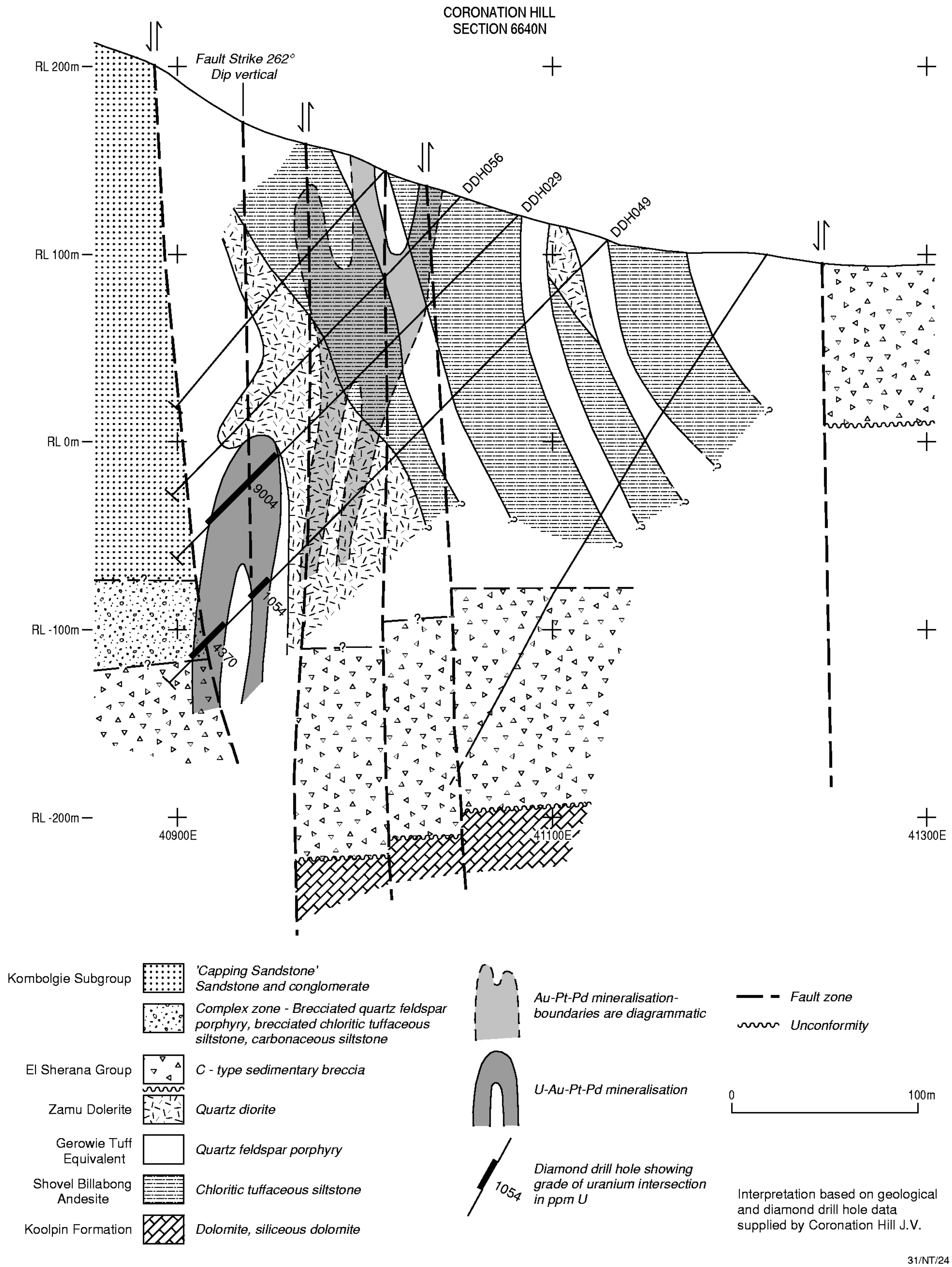

Figure 22. Coronation Hill deposit, cross-section 6640N, showing zones of mineralisation

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)

<table>
<tr><td>THROSSELL GROUP</td><td colspan="2">Basal member is the Coolbro Sandstone — sandstone, minor siltstone, basal conglomerate</td></tr>
<tr><td colspan="3">Unconformity, commonly tectonised</td></tr>
<tr><td rowspan="4">RUDALL COMPLEX</td><td>Orthogneiss</td><td>Metamorphosed granitoids (1787–1765 Ma)</td></tr>
<tr><td colspan="2">Intrusive contact, tectonised</td></tr>
<tr><td>Metasedimentary rocks</td><td>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)</td></tr>
<tr><td>Orthogneiss</td><td>Complex lithologically layered orthogneiss, crystallised at about 2015 Ma</td></tr>
</table>

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).

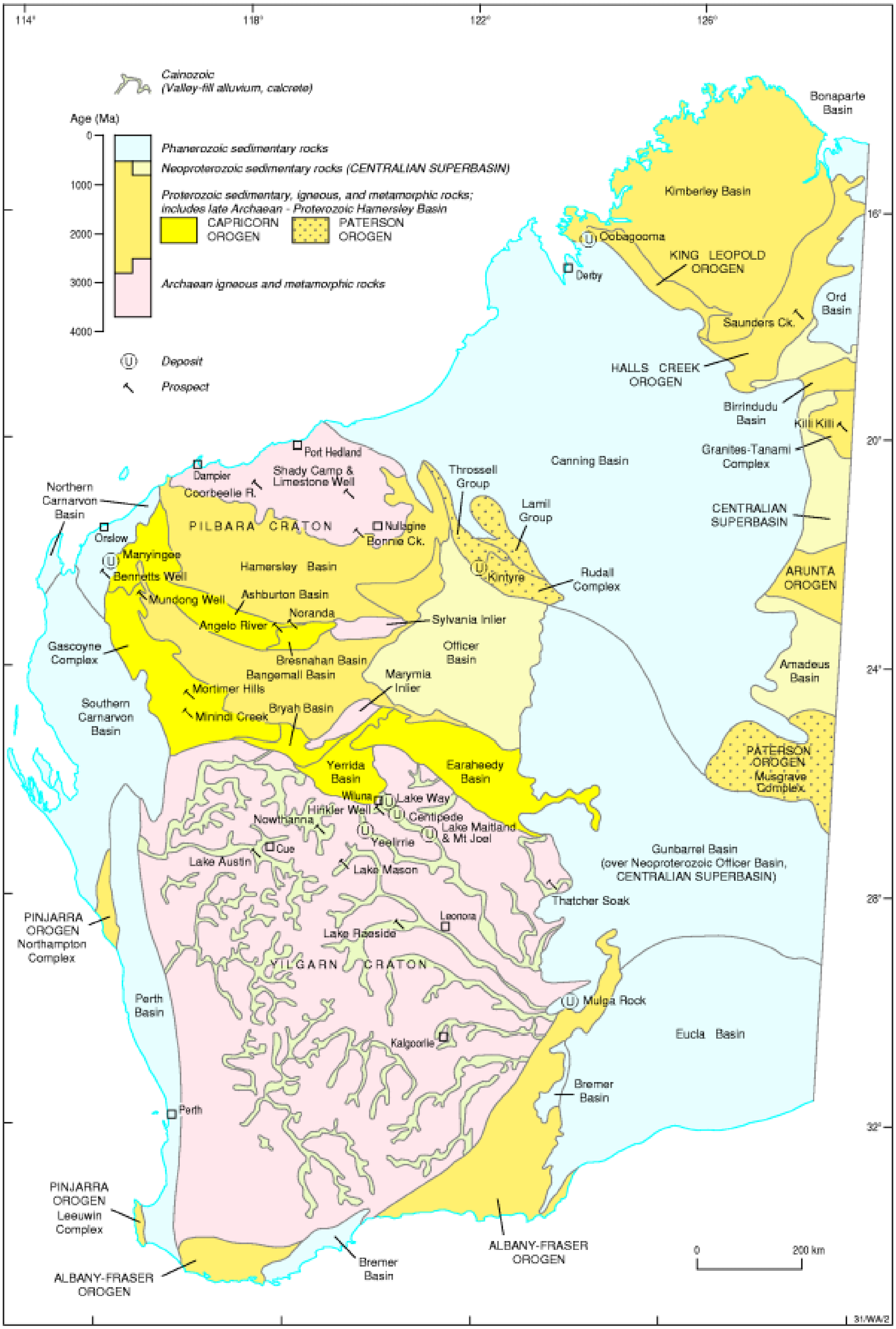

Figure 23. Geological provinces of Western Australia, and locations of uranium deposits and prospects (Tertiary drainage channels are shown only on the Yilgarn Craton). Geological map prepared by Geological Survey of Western Australia.

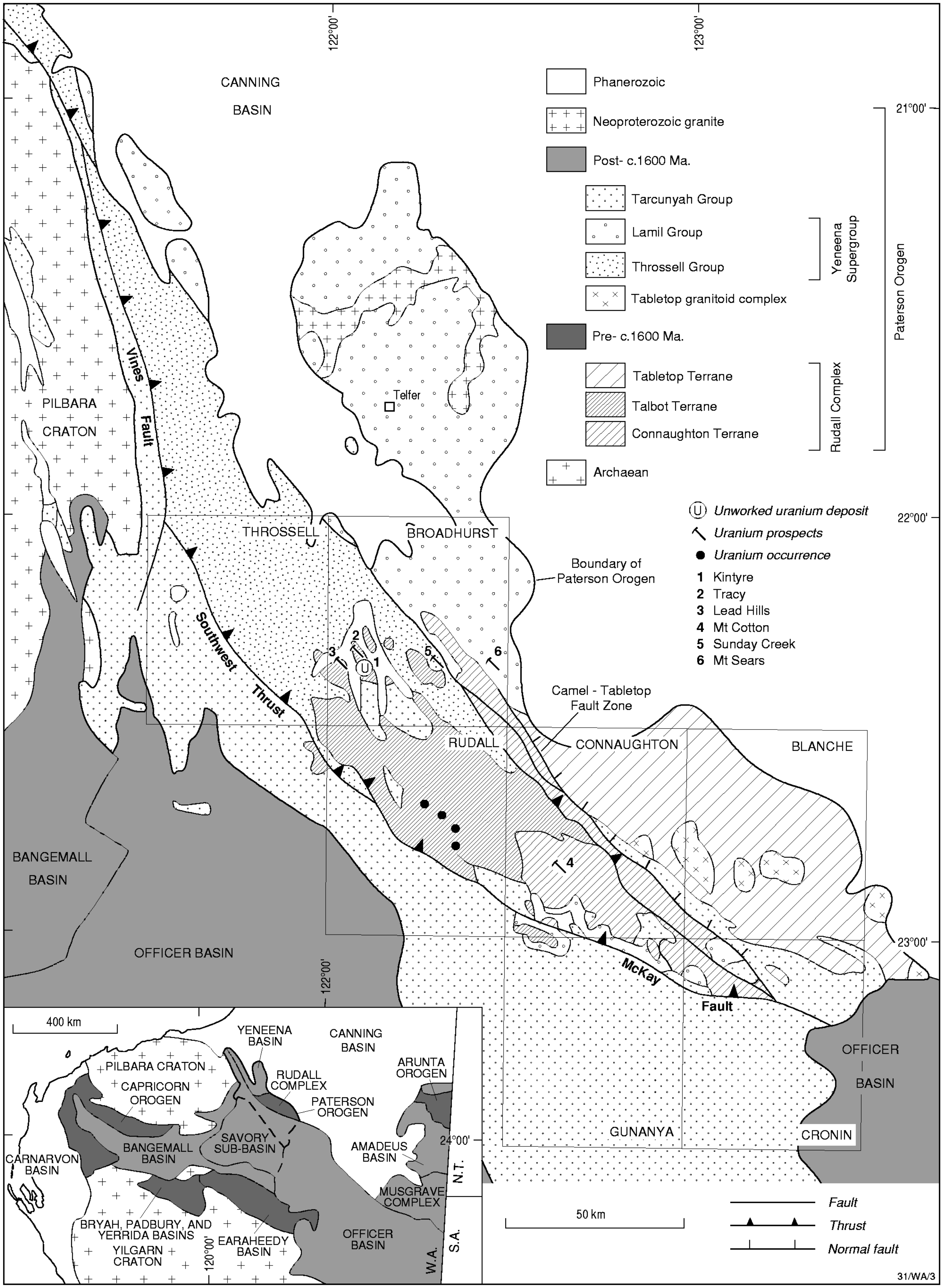

Figure 24. Regional geology of the Rudall Complex and the Yeneena Basin, and locations of uranium deposits and prospects (regional geology after Hickman & Bagas, 1999)

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).

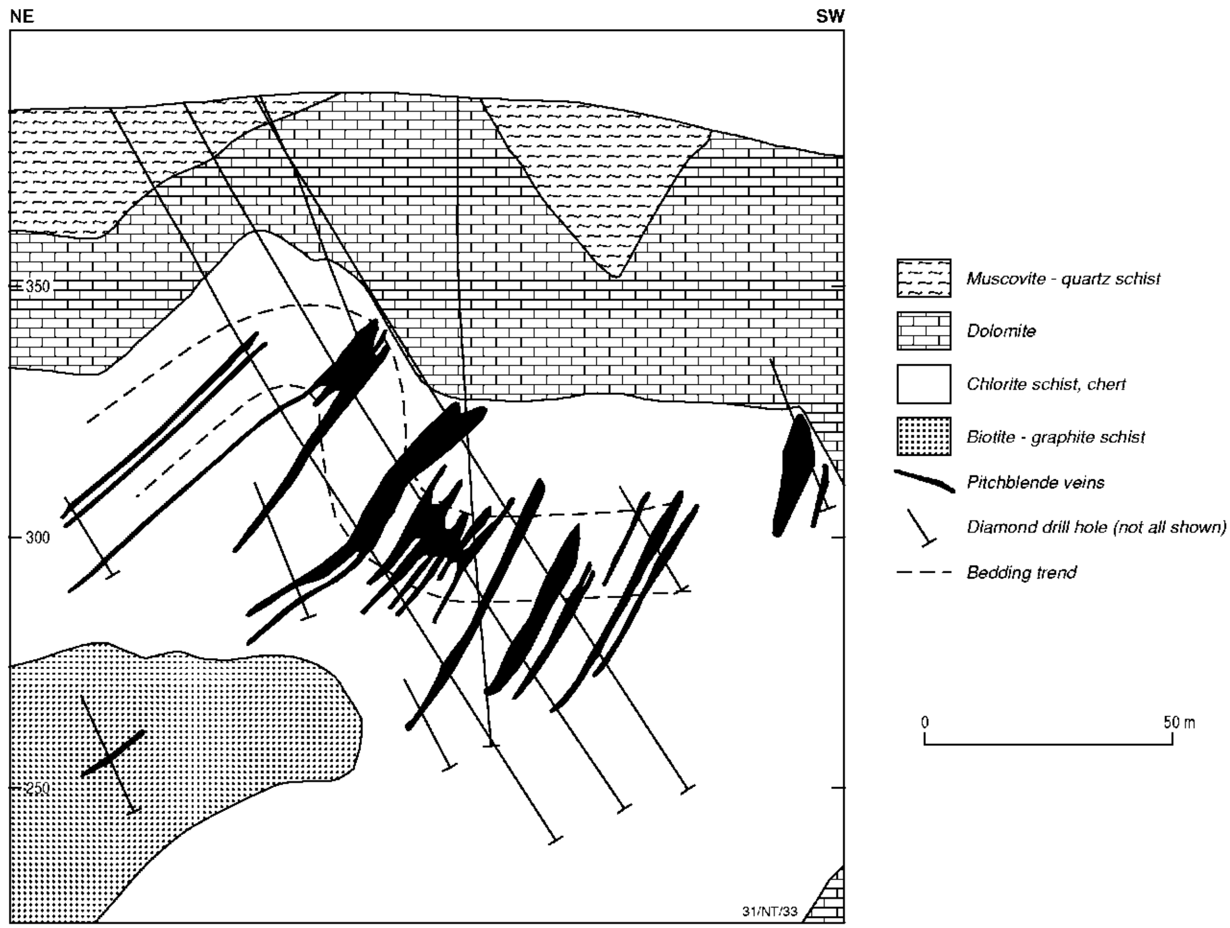

Figure 25. Section through the Kintyre deposit, drawn looking to south-east. The section is at right angles to the veins and oblique to the strike of metasediments and the drilling grid (after Gauci, 1997).

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).