Resource Report 1

Australian uranium resources

G.C. Battey, Y. Miezitis & A.D. McKay

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

DEPARTMENT OF RESOURCES & ENERGY

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G.C. BATTEY, Y. MIEZITIS, & A.D. McKAY
(Resource Assessment Division)

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FOREWORD

This is the first of a new series of Resource Reports to be published by the Bureau of Mineral Resources. Reports in this series will be essentially compilations of information about mineral resources in Australia and its Territories. It is planned that they will provide summaries of information, including a very complete bibliography, on significant deposits, so that companies and individuals interested in Australia's mineral resources will look to them as a prime source or a starting point for research.

Australia's uranium resources were chosen as the subject of the first report because it was considered to be an appropriate time to draw together information on Australia's widespread and diverse types of uranium deposits, which currently account for about 29% of the WOCA countries' Reasonably Assured Resources in the low-cost category. The report provides a brief overview of uranium exploration, production, resources, deposit types, and potential for further discoveries, together with descriptions of the major deposits in all of Australia's known uranium fields.

(L.C. Ranford)
First Assistant Director,
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ABSTRACT

Australia's uranium resources amount to 29% of the WOCA* countries' (WOCA: world outside centrally-planned-economies areas) low-cost Reasonably Assured Resources and 28% of the WOCA countries' low-cost Estimated Additional Resources (category I). As at 1 January 1986, BMR estimated Australia's uranium resources as:

— *Cost range to US$80/kg U (US$30/lb U_3O_8)*
  Reasonably Assured Resources, 465 000 t U
  Estimated Additional Resources — Category I, 256 000 t U

— *Cost range US$80–130/kg U (US$30–50/lb U_3O_8)*
  Reasonably Assured Resources, 56 000 t U
  Estimated Additional Resources — Category I, 127 000 t U

Most resources are contained in Proterozoic unconformity-related deposits in the Alligator Rivers uranium field in the Northern Territory (Jabiluka, Ranger, Koongarra, Nabarlek deposits) and the Proterozoic stratabound deposit at Olympic Dam on the Stuart Shelf in South Australia. The rest are mainly contained in Cainozoic surficial calcrete deposits in central Western Australia. Australia has only relatively minor resources of sandstone-type deposits and no pebble-conglomerate type deposits, which together constitute a major proportion of world resources. Between 1954 and 1971, 7810 t of U was produced in Australia. Production was resumed in 1976 and Australia's share of WOCA countries' production has increased from 1.2% (356 t U) in 1977 to 9.2% (3206 t U) in 1985. Several Australian uranium deposits are only partly delineated. The intensity of exploration in Australia has been lower than that in other countries with substantial uranium resources, and the potential for further discoveries remains very high.

INTRODUCTION

The uranium industry has developed during the past forty years. From 1943 to 1965 it was developed mainly for the defence programs of USA, UK, USSR, and France. The principal use of uranium now and in the foreseeable future is as the fuel source for nuclear power stations, and the industry is therefore supported by the requirements of the world's commercial nuclear power programs (Silver, 1981). Nuclear power stations are providing an increasing proportion of the world's electricity requirements. This is the result of decisions made in the 1970s during a sustained period of rapidly increasing oil prices that placed the economies of many countries under pressure. Requirements for this purpose are estimated by the OECD-Nuclear Energy Agency & International Atomic Energy Agency (OECD-NEA & IAEA, 1986) as 41 000 t U in 1986, 48 000 t U in 1990, and 55 000 t U in 1995. The commercial introduction of fast-breeder reactors in the next century could reduce the need for increases in uranium production because fast-breeder reactors can produce as much fissile material as they consume.

Uranium — a hard, white metal with a specific gravity of 18.7 and atomic number 92 — was discovered by Martin Klaproth in 1789 and was first extracted as a metal by Eugene Melchior Peligot in 1841. In 1896, Henri Becquerel discovered that uranium undergoes radioactive decay. The phenomenon of nuclear fission was recognised by Otto Hahn and Fritz Strassmann in 1938 and uranium became a substance of major scientific, and eventually economic, interest.

As found in nature, the element uranium is a mixture of three isotopes: U^{234} (0.01%), U^{235} (0.71%), and U^{238} (99.28%). Of these, only uranium 235 is fissile — indeed, uranium 235 is the only naturally occurring fissile substance. Uranium 238 can be used to produce the fissile element, plutonium, whereas uranium 234 is a non-fissile alpha-emitter of no practical importance.

Uranium does not occur in the native state. Some hundreds of uranium-bearing minerals have been identified, but only a few are of commercial significance. The principal ore mineral is uraninite (known as pitchblende when massive). Uranium is one of the less abundant elements, although it is widely distributed in the earth's crust. It is as abundant as molybdenum, tin, and tungsten, and more abundant than mercury, antimony, and silver. Uranium is also present in sea water, at a concentration of 0.003 ppm, and it is technically, although not yet economically, feasible to extract it from sea water.

Under certain conditions the nucleus of the uranium isotope U^{235} can be split into two halves of roughly equal mass. This splitting, termed fission, releases an enormous amount of energy which is being used in nuclear reactors to provide an increasing proportion of the world's electricity requirements. The main reactor type in use and under construction throughout the Western world is the Light-Water Reactor.

Because of its density, depleted uranium (i.e. uranium depleted in the U^{235} isotope as a result of enrichment) is used as a shielding medium against radiation and as counterweights, particularly in aircraft. It is also used as a catalyst and as a colouring medium in ceramics.

Uranium is a source of radiation for the production of radioactive isotopes used in medicine. Also, irradiation using uranium as an indirect source is being investigated as a means of preserving food.

The uranium industry, from exploration, through mining, milling, enrichment, and use, to the disposal of radioactive waste, is commonly referred to as the 'nuclear fuel cycle'. Uranium ore is mined and milled to produce a uranium oxide concentrate — 'yellowcake'. Modern milling technology produces a calcined concentrate with a uranium content greater than 75%. The uranium oxide is referred to as 'U_3O_8', although it may be present as a mixed oxide (UO_2/UO_3). Uranium is normally traded in the form of concentrate, the selling units being lbs U_3O_8 (\$/lb U_3O_8) or kg U (\$/kg U).

Australian activity in the nuclear fuel cycle is confined largely to exploration for deposits of uranium, mining and milling of uranium ores, transport and export of yellowcake and other materials produced, and handling and disposal of mill tailings. The Commonwealth Government operates a small reactor at Lucas Heights, near Sydney, for research and the production of isotopes and radiopharmaceuticals for medical use. Australia is a signatory to international agreements relating to the use of nuclear materials and the prevention of nuclear weapons proliferation.

The nuclear fuel cycle and proposals for the development of Australian mines were considered in detail by the Ranger Uranium Environmental Inquiry, under Mr Justice Fox, between 1975 and 1977 (Fox & others, 1976 & 1977). Australia's role in the nuclear fuel cycle was investigated by the Australian Science & Technology Council (ASTEC) (1984), under Professor R.O. Slatyer, during 1983 and 1984, and in 1985 the Australian Government announced its response to the recommendations of the ASTEC report. It was stated that the mining and export of uranium would be continued subject to 'strict safeguards conditions, but only from the Nabarlek, Ranger, and Olympic Dam mines'.

In Australia, uranium exploration intensified during the late 1970s and reached a peak in 1980–81 (Table 1). This led to a rapid increase in the volume of data and knowledge on uranium resources. Now is an appropriate time to summarise the available information and to update the report on uranium deposits prepared by Ingram (1974).

The information in this report has been obtained from published reports and open-file exploration reports, and from the personal experience and knowledge of the authors.

Acknowledgements

Assistance in the preparation of this report was provided by many individuals in the State Mines Departments and their equivalents, the mining companies, and the universities, and is gratefully acknowledged. The authors would also like to thank BMR colleagues, especially R.S. Needham, D. Perkin, J.H.C. Bain, R.G. Dodson, I.R. McLeod, and John Ferguson, who critically read sections of the report. The manuscript was typed and keyboard-edited by B. McRae, F. Plunkett, Y. Aitken, and P. Nambiar.

Table 1. Second exploration phase, 1967 to the present: expenditure and amount of drilling

	Expenditure ($ million, current dollars)	*Drilling ('000 m)*
1967	1	n.a.
1968	3	n.a.
1969	6	n.a.
1970	8	n.a.
1971	9	n.a.
1972	13	n.a.
1973	11	n.a.
1974	11	n.a.
1975	8	65
1976	13	168
1977	17	240
1978	25	335
1979	29	274
1980	35	489
1981	38	425
1982	29	254
1983	14	101
1984	13	77
1985	13	56

n.a. — not available
Note: The aggregate amount of drilling from 1967 to 1971 was 573 000 m.

EXPLORATION

The occurrence of uranium in Australia was known long before the start of any systematic search for it. Uranium was recorded from Carcoar (NSW) in 1894, from Mount Painter (SA) in 1906 (Fig. 1), and from Radium Hill (SA) in 1910.

First phase (1944 to late 1950s)

Exploration in Australia started in 1944 at the request of the United Kingdom and United States governments. The known deposits at Mount Painter and Radium Hill were re-examined and, in 1948, to promote exploration, the Commonwealth Government offered tax-free rewards for the discovery of uranium orebodies. This stimulated the search, particularly around known mineral fields. Portable geiger counters enabled even the most inexperienced amateurs to compete with experienced prospectors and with professionally-led company exploration teams. In some areas there was feverish activity akin to the gold rushes of last century. Uranium was discovered at Rum Jungle (NT) in 1949, in the South Alligator valley (NT) in 1953, at Mary Kathleen (Qld) in 1954, and at Westmoreland (Qld) in 1956. Minor occurrences were found at many places across the continent. Sums totalling about $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).

Second phase (late 1960s to the present)

Exploration was revived in the late 1960s (Table 1) with the prospect of increased demand for uranium for power generation. When this increase eventuated, in the mid 1970s, there was a sharp rise in prices on the spot market (Fig. 2). The spot market for uranium accounts for 5–15% of international sales. Prices also rose sharply for long-term sales contracts, under which most uranium sales are made (Fig. 3). By the late 1960s there was a much better understanding of the distribution of uranium, and the search could be focused more effectively on geological environments considered likely to contain significant uranium mineralisation. 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 with the more sophisticated spectrometers that had by then become available.

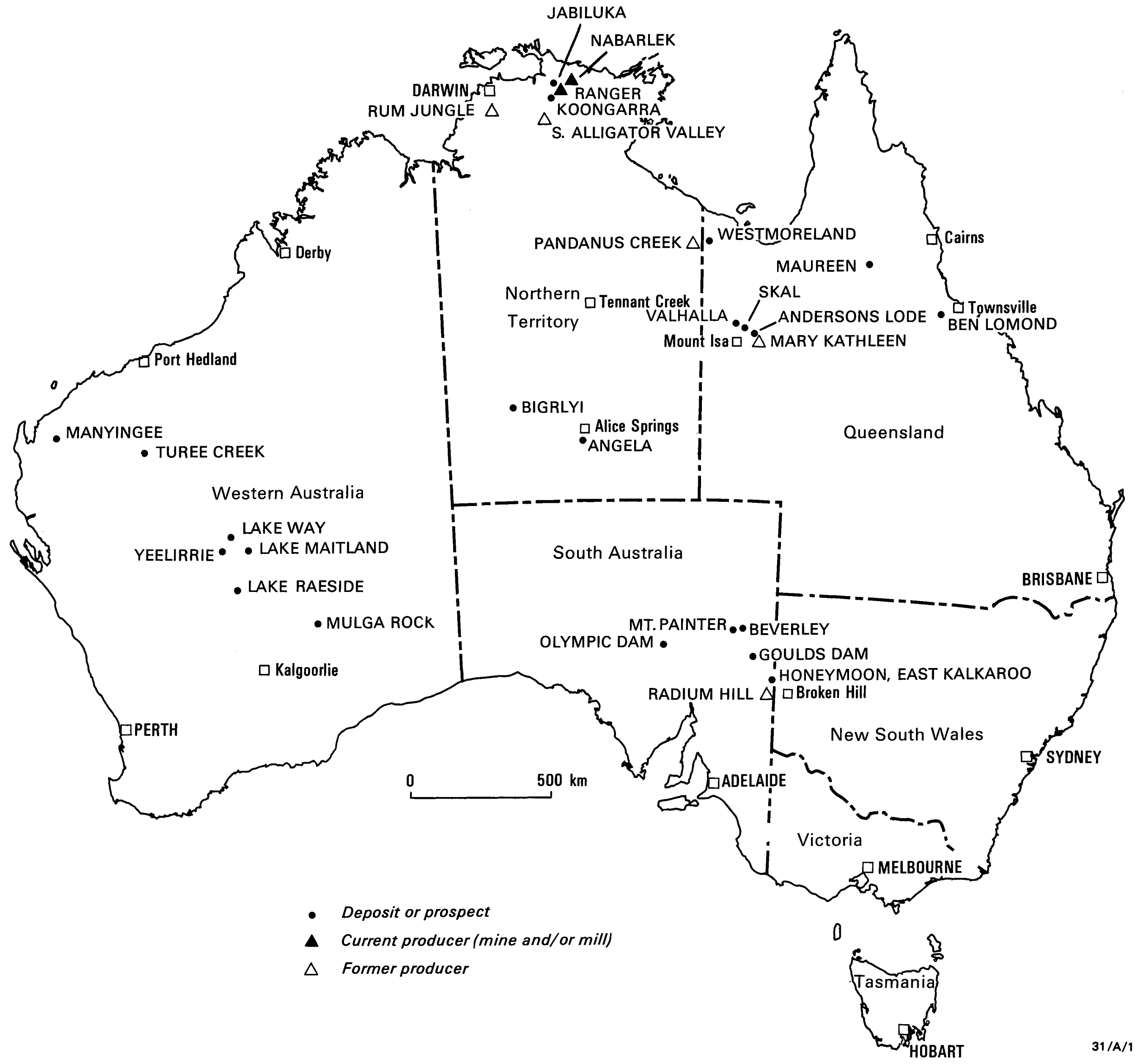

Fig. 1. Australian uranium deposits and prospects.

Within a span of seven years several significant discoveries were reported — Beverley (SA) in 1969; Ranger (NT), Nabarlek (NT), Koongarra (NT), and Bigrlyi (NT) in 1970; Jabiluka (NT), Honeymoon (SA), and Maureen (Qld) in 1971; Yeelirrie (WA) in 1972; Angela (NT) in 1973; and Olympic Dam (SA) and Ben Lomond (Qld) in 1975. Most of them, in contrast with those of the earlier exploration period, were made as a result of the investigation of radiometric anomalies delineated by airborne radiometric surveys conducted by professional exploration teams employed by companies.

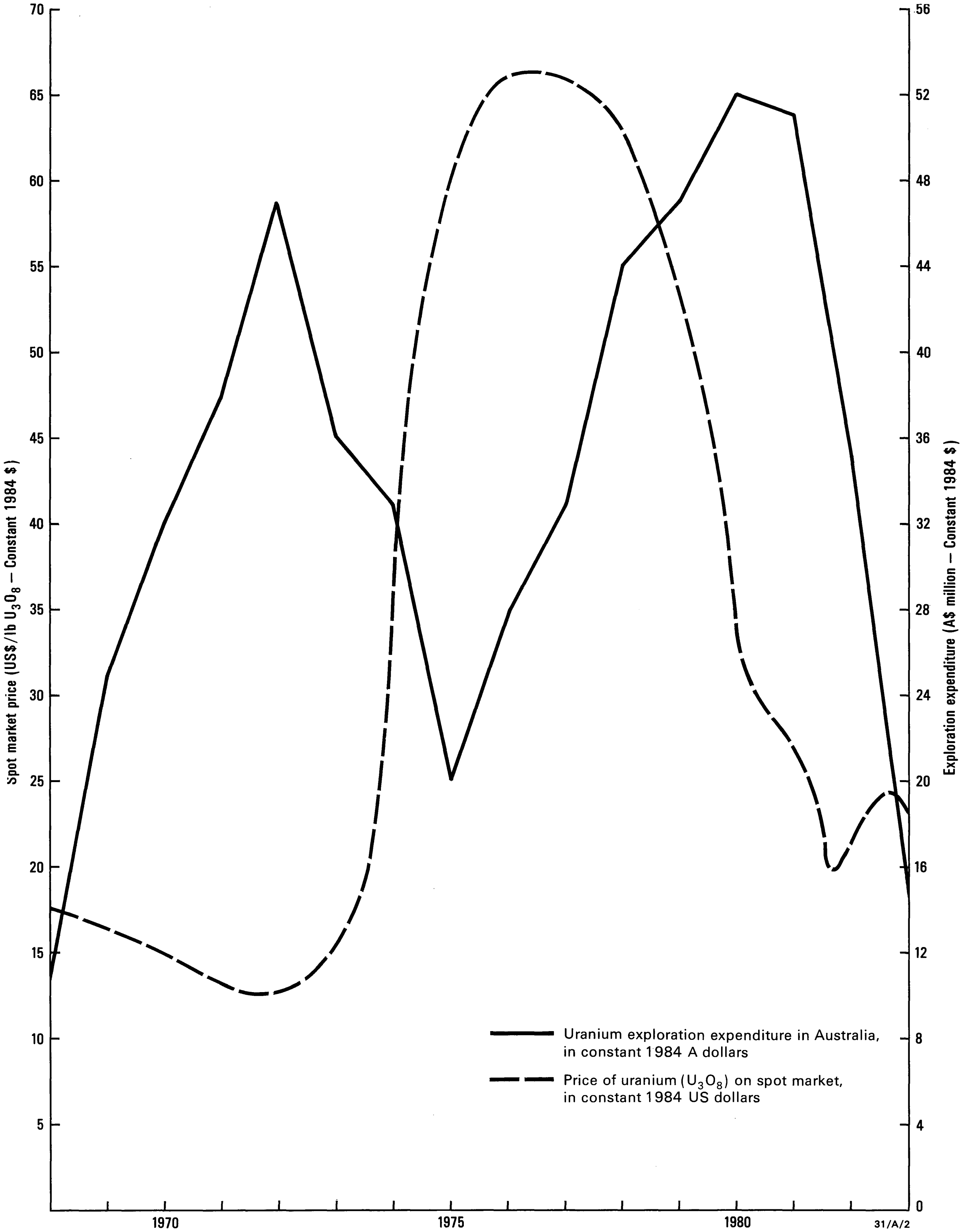

Fig. 2. **U_3O_8 spot-market prices, and annual expenditure on uranium exploration in Australia, 1968–83 (spot-market price curve from OECD-NEA, 1985).**

In constant-dollar terms, expenditure on uranium exploration between 1968 and 1984 peaked in 1972 and again in 1980 (Fig. 2).

The success of uranium exploration in Australia is best illustrated by the cost of discovery/kg U, which is significantly lower than in other countries.

The deposits containing most of Australia's resources were found between 1969 and 1975. Since then, a large proportion of exploration expenditure has been directed at delineating resources in known deposits. This has resulted in very substantial increases in Australia's uranium resources.

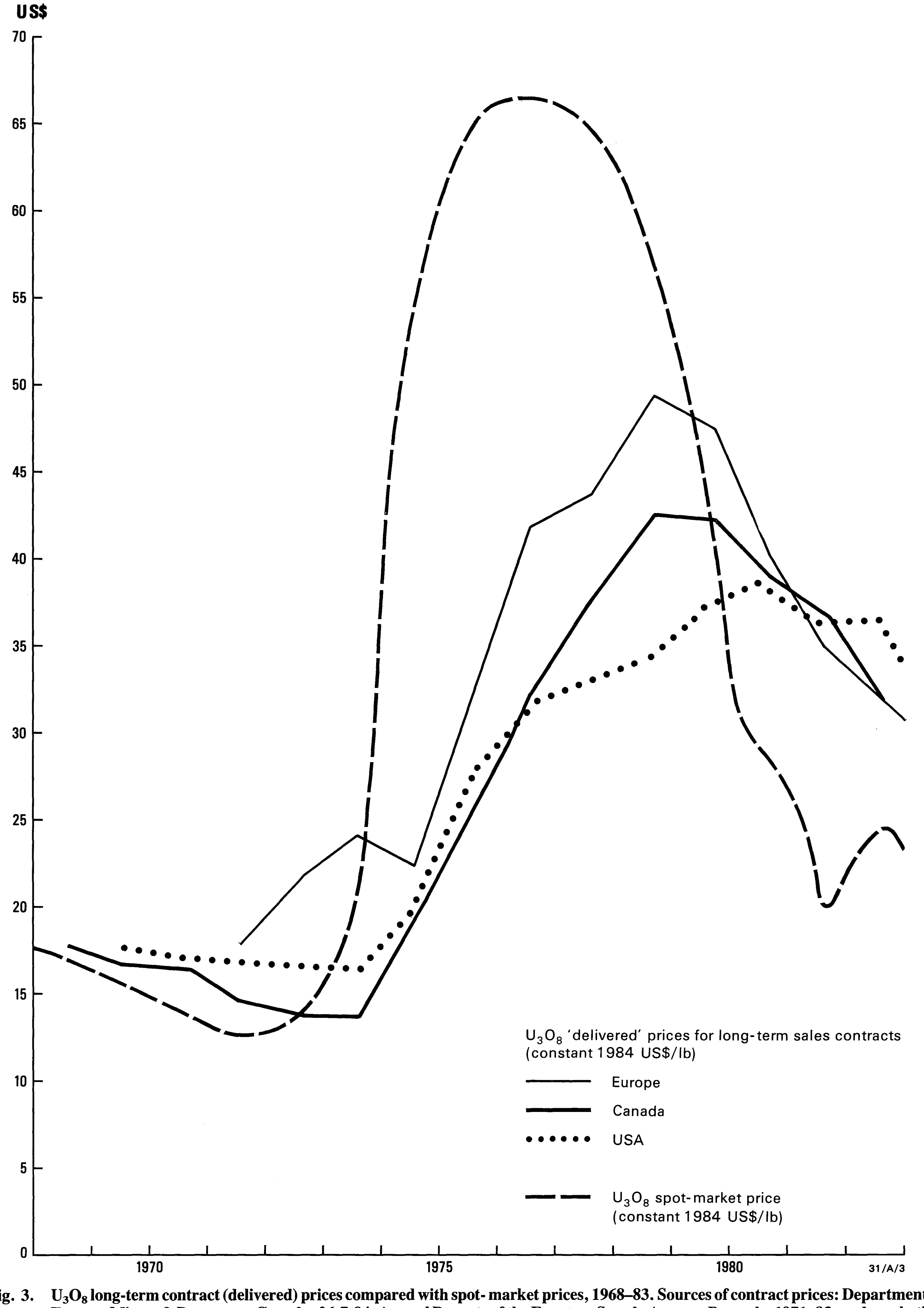

Fig. 3. U_3O_8 long-term contract (delivered) prices compared with spot- market prices, 1968–83. Sources of contract prices: Department of Energy, Mines, & Resources, Canada, 26.7.84; Annual Reports of the Euratom Supply Agency, Brussels, 1971–83; and marketing surveys of the US Atomic Energy Commission, US Energy Research & Development Administration, and US Department of Energy, 1968–84. Spot-market price curve from OECD-NEA (1985).

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 of ore was treated, and the uranium content had minor commercial interest for use in ceramic glazes. Only a fraction of the uranium content of the ore was recovered. This production can be considered as insignificant.

First phase (1954 to 1971)

Between 1954 and 1971 Australia produced some 7800 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 (CDA) — the joint UK/USA uranium purchasing agency. Capital investment in mining and treatment amounted to about $50 million, and exports earned some $164 million.

Rum Jungle, the first Australian producer, 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). An agreement was signed with CDA for the purchase of 1255 t U over a ten-year period on a cost-plus basis. Subsequent production was retained by the Australian Atomic Energy Commission (AAEC) 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. It used sulphuric acid to leach the ore and, up to 1962, employed ion-exchange to separate the uranium. Magnesia was used 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).

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 taken to a treatment plant at Port Pirie designed to produce 136 t U/year.

Mary Kathleen was operated by Mary Kathleen Uranium Ltd as an open-cut mine to supply 3460 t U to the UKAEA. The mill had a nominal capacity of 760 t U/year. Before fine grinding, 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.

United Uranium NL acquired an old gold treatment plant at Moline, some 65 km west-southwest 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 from 1959 to 1966. 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 of 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.

The first phase of uranium production in Australia ceased after the closure of the Rum Jungle plant in 1971.

Second phase (1976 to the present)

Uranium production in Australia resumed in 1976 (Table 3), at the Mary Kathleen mine. Production started at the Nabarlek mine in June 1980 and at Ranger in August 1981.

When the **Mary Kathleen** plant was recommissioned in 1976, solvent extraction was preferred to ion-exchange because of lower operating costs. The mine was continued as an open cut. After producing enough yellowcake to satisfy existing contracts, the plant was closed in October 1982, as no more contracts could be obtained at prices that would justify further production. The plant and equipment were sold and dismantled, and the remaining resource (1200 t U_3O_8) is unlikely ever to justify development.

Table 2. First production phase, 1954–1971

	Rum Jungle (NT)	*Radium Hill (SA)(c)*	*Mary Kathleen (Qld)*	*South Alligator valley (NT)* United Uranium NL	*South Alligator valley (NT)* 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(g)	13 500
Average grade (% U)	0.24–0.34(b)	0.59–0.76(d)	0.20(f)	0.30–0.58(h)	0.95
Production (t U)	2993	721	3460	441(h)	117
Export contract					
Purchaser	CDA	CDA	UKAEA	UKAEA(i)	UKAEA
Quantity (t U)	1255	721	3460	441(i)	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 was 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 concentrate treated at Port Pirie; run-of-mine ore averaged 0.09–0.13% U.
(f) Average grade of ore. After radiometric ore sorting; run-of-mine ore averaged 0.13% U.
(g) Excludes ore used to produce pitchblende concentrate and subsequently custom treated at Rum Jungle.
(h) Excludes ore used to produce pitchblende concentrate.
(i) In addition, UUNL supplied 150 t of pitchblende concentrate containing 70 t U to the CDA.

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

	Mary Kathleen(a)	*Nabarlek(b)*	*Ranger(c)*	*Annual total(d)*
1976	359	—	—	359
1977	356	—	—	356
1978	516	—	—	516
1979	705	—	—	705
1980	708	853	—	1561
1981	699	1209	952	2922
1982	728	1067	2658	4422
1983	—	1029	2188	3211
1984	—	1188	3202	4324
1985	—	1115	2136	3206

Sources:

(a) MKU Ltd annual reports; final statements and production reports; 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) Australian Bureau of Statistics (ABS).

Note: The Mines departments in Queensland and the Northern Territory gather data on total annual uranium production for each mine; these data are supplied to ABS, which aggregates them and publishes only the total annual production. The total annual production (ABS) figures for certain years differ from the total of the amounts produced from each mine as reported by the companies to the Stock Exchange; the discrepancies are due to slightly different accounting periods for the four quarterly figures and the annual figures, and different factors used in calculating the total amount of contained uranium in the concentrate produced in particular periods.

The **Nabarlek** orebody was mined by open pit in 1979 and stockpiled for treatment. The plant began operating in 1980. The ore is leached by sulphuric acid. Pyrolusite was originally used as the oxidant, but this was subsequently replaced by Caro's acid to reduce the consumption of reagents (Lucas, Fulton, Vautier, Waters, & Ring, 1983). The uranium is separated by solvent extraction and precipitated by ammonia. The mill has a nominal capacity to treat 170 t of ore/day to produce 915 t U/year; however, in some three-month periods production rates as high as 1370 t U/year have been achieved.

The **Ranger** No. 1 orebody is mined by open pit. The ore is leached by sulphuric acid (manufactured on site from imported sulphur) and the uranium is separated by solvent extraction and precipitated by ammonia. Production rates as high as 3520 t U/year were achieved over three-month periods during 1984. The nominal capacity of the Ranger mill was recently increased from 2540 t U/year to 3220 t U/year (1.15 Mt ore/year).

Existing and proposed Australian uranium treatment plants are described in *'Uranium Extraction Technology'* (OECD-NEA & IAEA, 1983b).

Although Australia has 29% of the Low-cost Reasonably Assured Resources of the WOCA countries, Australian production represents only a small proportion of world production to date. WOCA cumulative uranium production to the end of 1985 was 812 164 t U, of which Australia produced 29 382 t, or less than 4%. The major producers have been USA, Canada, and South Africa, and production from France, Niger, and Namibia has exceeded Australian production (Table 4).

Table 4. Mine production of uranium, WOCA countries (t U)

	pre-1980	*1980*	*1981*	*1982*	*1983*	*1984*	*1985*	*Totals to date*
Australia (a)	9 736	1 561	2 922	4 422	3 211	4 324	3 206	29 382
Canada	131 490	7 150	7 720	8 080	7 140	11 170	10 880(b)	183 630
France	29 775	2 634	2 552	2 859	3 271	3 168	3 200(b)	47 459
Gabon	11 493	1 033	1 022	970	1 006	918	935(c)	17 377
Namibia	9 471	4 042	3 971	3 776	3 719	3 700(e)	3 385(d)	32 064
Niger	13 397	4 128	4 363	4 259	3 426	3 276	3 181(c)	36 030
South Africa	87 450	6 146	6 131	5 816	6 060	5 732	5 000(e)	122 335
USA	249 828	16 804	14 793	10 331	8 135	5 722	4 352(b)	309 965
Zaire	25 600	0	0	0	0	0	0	25 600
Others	4 494	518	486	744	738	637	705	8 322
Totals	572 734	44 016	43 960	41 257	36 706	38 647	34 844	812 164

Sources: OECD-NEA & IAEA (1986), and the following, as indicated ('e' = estimated):
(a) *Australian Mineral Industry Quarterly;* (b) OECD-NEA (1986); (c) Commissariat a l'Energie Atomique (1985); (d) Nukem (1986).

CLASSIFICATION OF DEPOSIT TYPES

The Joint Steering Group on Uranium Resources of OECD-NEA & IAEA (1978) classified uranium deposits according to their geological setting, and identified six categories. The Group added another category — surficial deposits — in 1983. Their classification as thus amended is:

1. Quartz-pebble conglomerate deposits
2. Proterozoic unconformity-related deposits
3. Disseminated magmatic, pegmatitic and contact deposits in igneous and metamorphic rocks
4. Vein deposits
5. Sandstone deposits
6. Surficial deposits
7. Other types of deposits

These categories were modified further in IAEA-TECDOC-315, edited by Ferguson (1984a). The Proterozoic unconformity-related deposits were subdivided into:

— stratiform and stratabound types, and
— unconformity-related types.

Both of these sub-categories contain important uranium deposits, and the differences between them are so great, as for example between Olympic Dam and the Alligator Rivers deposits, that in this report they are elevated to separate categories, 'Proterozoic unconformity-related deposits' and 'Proterozoic stratiform and stratabound deposits'. In effect, this classification conforms with that adopted by OECD-NEA & IAEA (1983), with the addition of an extra category.

The various deposit types are described below in an order that approximates their decreasing order of significance as known in Australia today.

Proterozoic unconformity-related deposits

These deposits occur close to major unconformities that developed after a worldwide deformational epoch at about 1800–1600 Ma. They are confined to regions where Archaean basement and Early Proterozoic metasediments are unconformably overlain by Middle Proterozoic sandstone that in most places remains flat-lying and relatively undisturbed. The deposits are in the Early Proterozoic sequences, usually within a few hundred metres of the overlying unconformity, although in the Athabasca Basin in Canada some orebodies are in the Middle Proterozoic cover, directly above the unconformity.

Host rocks are schist and occasionally pelitic gneiss. The uranium deposits in each province or field are stratabound. Within the favourable host rocks, the uranium mineralisation is in open structures in zones of fracturing, shearing, and brecciation. Alteration, chiefly chloritisation, is common and is contemporaneous with uranium mineralisation.

The Middle Proterozoic cover rocks are mainly coarse, porous quartz sandstone and minor conglomerate, siltstone, and shale.

Proterozoic unconformity-related deposits include some of the largest and richest known uranium deposits, ranging in grade from 0.3% U_3O_8 to over 10% U_3O_8, and constitute a major proportion of the world's known resources. Major deposits of this type include Cluff Lake, Key Lake, Rabbit Lake, Midwest Lake, and Cigar Lake in the Athabasca Basin of northern Saskatchewan, and those of the Pine Creek Geosyncline in the Alligator Rivers uranium field.

A major proportion of Australia's uranium resources is contained in this type of deposit (Table 5) and most of Australia's uranium production since 1980 has been from two of them — Ranger 1 and Nabarlek. Other large deposits of this type in the Alligator Rivers uranium field are Jabiluka, Koongarra, and Ranger 68. 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 Geosyncline, the unconformity broadly coincides with much of the present land surface. The Middle Proterozoic sandstone is flat-lying and forms a prominent plateau and escarpment. The uranium deposits are near this escarpment, but it is not suggested in this report that this controls the localisation of the mineralisation.

In the Alligator Rivers, Rum Jungle, and South Alligator Valley uranium fields, the uranium 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 Early Proterozoic sedimentary rocks nearby (Ewers & others, 1984) (Fig. 5).

Field relationships and age-dates show that the main mineralisation in the Pine Creek Geosyncline followed the 1800 Ma regional metamorphism. The mineralisation was remobilised, probably several times (Ewers, Ferguson, Needham, & Donnelly, 1984).

Dating of uraninite and galena indicates two main periods of mineralisation or mobilisation, at about 1600 and 900 Ma (Hills & Richards, 1976; Page, Compston, & Needham, 1980).

Proterozoic stratiform and stratabound deposits

These deposits occur in Early and Middle Proterozoic rocks, the largest known worldwide being in Middle Proterozoic sedimentary strata (Ferguson, 1984b). The uranium mineralisation is in basal strata unconformably overlying high-uranium granitoids of the basement complexes.

No spatial relationship between the mineralisation and any overlying unconformity surface has been recorded.

The depositional environment of the host rocks was anorogenic and related to extensional tectonics, and in several cases the mineralisation appears to have been deposited in a rift valley. The initial mineralisation in this type of deposit is usually stratiform, and later developments of epigenetic mineralisation are related to fractures and faults.

The largest known deposits of this type are at Olympic Dam in Australia, the Aillik Group in Labrador, and in Zambia and Zaire.

Deposits in this category make up a major proportion of Australia's uranium resources (Table 5). The Olympic Dam deposit is a very large copper-uranium-gold-silver deposit in Middle Proterozoic rocks that form the basement to the Stuart Shelf. The host rocks are unmetamorphosed sedimentary breccias occupying a northwest-trending graben. The rock types range from matrix-poor granite breccias to matrix-rich polymict breccias, the matrix being mainly hematite.

Sandstone deposits

Uranium deposits of this type are contained in fluvial or marginal-marine sandstone. The host rock is medium-to coarse-grained and poorly-sorted, and contains 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 & others, 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 rate of groundwater movement and oxygen intake is slowed enough to preclude destruction of reducing environments. Beds with low dips also provide a large surface area for capture and introduction of uraniferous groundwater.

Deposits in this category contain a large proportion of the world's known uranium resources. In each province or basin there are usually many relatively small deposits, but the cumulative tonnage in the province or basin is often very large. Major sandstone uranium provinces include the Wyoming Basin, Colorado Plateau, and Gulf Coastal Plain of the USA, and the Tim Mersoi Basin of Niger.

Sandstone uranium deposits comprise a significant proportion of Australia's total uranium resources (Table 5). Large deposits of this type occur in the Frome Embayment (Beverley), Officer Basin (Mulga Rock), and McArthur Basin (Westmoreland). Smaller deposits occur in the Frome Embayment (Honeymoon, East Kalkaroo, Yarramba, and Gould's Dam), Ngalia Basin (Bigrlyi and Walbiri), Amadeus Basin (Angela and Pamela), Carnarvon Basin (Manyingee), and Canning Basin (Oobagooma). Large areas of low-grade uranium mineralisation are known in Eocene palaeochannel sediments northwest of the Eyre Peninsula in the Malbooma and Wynbring areas, and in several areas southwest of the Gawler Ranges.

In 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 deposits.

Table 5. Resources (U_3O_8) in Australian uranium deposits, as published by companies

	Proved & probable		*Possible*		*Unspecified*		
	Grade (%)	*Tonnes*	*Grade (%)*	*Tonnes*	*Grade (%)*	*Tonnes*	*References, comments*
PROTEROZOIC UNCONFORMITY-RELATED DEPOSITS							
Alligator Rivers uranium field							
Jabiluka 1	0.25	3 400	—	—	—	—	In situ
Jabiluka 2	0.39	204 000	—	—	—	—	Pancontinental Mining Ltd (1979)
Ranger 1							
No. 1 Orebody	0.322	38 815	—	—	—	—	Mostly in situ; includes stockpiled ore; Energy Resources of Australia Ltd (1986)
No. 3 Orebody	0.207	72 838	0.163	12 213	—	—	In situ; Energy Resources of Australia Ltd (1986)
Koongarra							
No. 1 Orebody	0.269	13 300	—	—	—	—	Mineable; Noranda Australia Ltd (1978)
No. 2 Orebody	—	2 300	—	—	—	—	In situ; Noranda Australia Ltd (1979)
Nabarlek	1.84	773	—	—	—	—	Resource figure as in EIS (Queensland Mines Ltd, 1979), less production to 30/6/86; the orebody was mined out and stockpiled in 1980
Hades Flat	—	—	—	—	—	726	Pancontinental Mining Ltd, 1977
Rum Jungle uranium field							
Mount Fitch	0.042	1 500	—	—	—	—	In situ; Berkman & Fraser (1980)
Turee Creek Area							
Angelo River 'A'	—	—	—	—	0.124	797	'Mineralisation'; Lustig & others (1984)
Sub-totals		336 926 (41.8%)(a)		12 213 (19.5%)(b)			
PROTEROZOIC STRATIFORM AND STRATABOUND DEPOSITS							
Stuart Shelf							
Olympic Dam	0.08	360 000	—	—	0.06	840 000	In situ; Western Mining Corporation Ltd announced an estimated tonnage for mineralised material in 1982, and the 'probable' ore resource figure in 1983; 'unspecified' resources have been derived here by subtracting the 1983 figure from the 1982 figure
Sub-totals		360 000 (44.6%)(a)					
SANDSTONE DEPOSITS							
Frome Embayment uranium field							
Beverley	0.27	16 200	—	—	—	—	In situ; South Australian Uranium Corporation (1983)
Honeymoon	0.157	3 390	—	—	—	—	In situ; Mines Administration Pty Ltd (1981)
East Kalkaroo	—	—	0.14	1 000	—	—	Sedimentary Uranium NL (1981)
Gould's Dam	—	—	—	1 100	—	—	In situ; CSR Ltd (1982)
Paralana–Pepegoona area	—	—	0.2	1 000	—	—	In situ; South Australia Department of Mines & Energy (1983)
Yarramba	Resources not reported						Brunt (1978)
Westmoreland–Pandanus Creek uranium field							
Westmoreland deposits	—	7 237	—	4 787	—	—	In situ; CSR Ltd (1982)
Ngalia Basin							
Bigrlyi	0.342	2 667	0.361	107	—	—	In situ; Central Pacific Minerals (1982)
Walbiri	—	—	0.162	686	—	—	In situ; Central Pacific Minerals (1976)
Amadeus Basin							
Angela and Pamela (combined)	—	—	—	7 700	—	—	In situ; includes both 'indicated' and 'inferred' categories; MIM Holdings Ltd (1980)
Officer Basin							
Mulga Rock	—	—	0.2	10 000	—	—	*Financial Review*, 15 June 1981
Carnarvon Basin							
Manyingee	Resources not reported						Valsardieu & others (1981)
Canning Basin							
Oobagooma	Resources not reported						Botten (1984)
Eyre Peninsula region							
Malbooma area	0.034	4 000	—	—	—	—	In situ; South Australia Department of Mines & Energy (1982a)
Sub-totals		33 494 (4.2%)(a)		26 380 (42.2%)(b)			

Table 5 (continued)

	Proved & probable		*Possible*		*Unspecified*		
	Grade (%)	*Tonnes*	*Grade (%)*	*Tonnes*	*Grade (%)*	*Tonnes*	*References, comments*
SURFICIAL (CALCRETE) DEPOSITS							
Yilgarn Block							
Yeelirrie	0.15	52 500	—	—	—	—	In situ; Western Mining Corporation Holdings Ltd (1982)
Lake Way	—	3 300	—	—	—	—	In situ resource at a cut-off grade of 0.055% U; French & Allen (1984)
Thatcher Soak	—	—	0.03	4 100	—	—	In situ; Cultus Pacific NL (1979)
Lake Mason	—	—	0.035	2 700	—	—	
Lake Raeside	—	—	0.025	1 700	—	—	
Lake Maitland	—	—	0.04	500	—	—	
Lake Maitland (Mount Joel)	—	—	—	3 500	—	—	In situ; MIM Holdings Ltd (1980).
Sub-totals		55 800 (6.9%)(a)		12 500 (20.0%)(b)			
DISSEMINATED MAGMATIC, PEGMATITIC AND CONTACT DEPOSITS IN IGNEOUS AND METAMORPHIC ROCKS							
Mary Kathleen–Mount Isa uranium field							
Mary Kathleen	—	—	—	1 200	—	—	In situ; Mary Kathleen Uranium Ltd (1981)
Elaine	—	—	0.06	100	—	—	Scott (1982)
Valhalla	0.19	3 810	0.20	1 663	—	—	In situ; Queensland Mines Ltd (1973)
Skal	—	—	0.13	3 447	—	—	In situ; Queensland Mines Ltd (1973)
Anderson's Lode	0.20	1 179	—	—	—	—	In situ; Queensland Mines Ltd (1973)
Olary uranium field							
Crocker Well	—	—	0.05	5 000	—	—	In situ; Ashley (1984)
Mount Victoria	0.315	207	—	—	—	—	In situ; North Flinders Mines Ltd (1979)
Mount Painter uranium field							
Hodgkinson	0.25	567	—	—	—	—	In situ; Exoil NL (1970)
Radium Ridge	0.06	2 177	—	—	—	—	
Mount Gee	0.10	2 722	—	—	—	—	
Armchair–Streitberg Ridge	0.10	1 814	—	—	—	—	
Sub-totals		12 476 (1.5%)(a)		11 410 (18.3%)(b)			
VEIN-TYPE DEPOSITS							
Georgetown–Townsville uranium field							
Maureen Deposit	0.123	2 940	—	—	—	—	In situ; Central Coast Exploration NL (1979)
Ben Lomond	0.247	4 758	—	—	—	—	In situ; Minatome Australia Pty Ltd (1983)
Twogee	—	—	—	—	0.1	640	In situ; Crane (1983)
Trident	—	—	—	—	0.2	420	In situ; Crane (1983)
Pine Creek Geosyncline							
Adelaide River	0.5	8	0.22	12	—	—	In stockpile and in-situ; Crohn (1968)
Sub-totals		7 706 (1.0%)(a)		12 (0.02%)(b)			
Total(c)		806 402		62 515			

(a) Percentage of total 'proved-and-probable' resource for this deposit type.
(b) Percentage of total 'possible' resource for this deposit type.
(c) BMR's calculated resource figures for individual uranium deposits are unavailable as they are classified as confidential. The resources shown in this table have been compiled from figures published by companies. The total proved-and-probable figure of 806 402 t U_3O_8 (in-situ) differs from BMR's 465 000 t recoverable U figure. For comparison, if one assumes a 50–95% mining recovery, 70–90% milling recovery, and U/U_3O_8 conversion factor of 0.848, the in-situ resource of 806 402 t U_3O_8 is equivalent to a recoverable resource of between 239 340 and 584 674 t U.

The larger Westmoreland deposits are in Middle Proterozoic sandstone along the southeastern 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. It is postulated that uranium was precipitated from oxygenated formation waters against physico-chemical barriers, such as basic flows or dykes, because of the abundant supply of divalent iron as reductant (Schindlmayr & Beerbaum, 1986).

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

The Mulga Rock deposit is in Tertiary sediments in an embayment along the southwestern margin of the Officer Basin.

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.

Surficial deposits

The calcrete-hosted deposits comprise the main surficial type. They formed under presumably semi-arid conditions where water movement was chiefly subterranean. The host rocks are fine-grained surficial sand and clay, partly cemented by calcrete and gypcrete. The calcium and magnesium carbonates accumulated in valley-fill sediment along Tertiary drainage channels eroded into the pre-Tertiary surface. Uranium was leached from the surrounding Archaean granite, transported by groundwater, and precipitated in the calcrete horizon to form large flat-lying accumulations of carnotite mineralisation.

The calcrete deposits comprise only a small proportion of the world's uranium resources. The largest known deposits are Yeelirrie in the Yilgarn area, WA, and Langer Heinrich in Namibia.

Other types of surficial uranium deposits are the 'bog-type' and 'young' deposits. Uneconomic deposits occur in some European peat bogs (Wilson, 1984). In Canada and the USA, significant 'young' deposits have been found in several types of organic-rich surficial environments (Otton, 1984; Culbert, Boyle & Levinson, 1984).

In southwestern Australia, carnotite mineralisation is widespread in calcreted trunk valleys of the Tertiary drainage systems and also occurs in playa lakes and terraces. The known deposits and significant prospects are confined to calcrete overlying Archaean granitic and greenstone basement of the northern Yilgarn Block.

Resources in this category make up a significant proportion of the Australian total. The Yeelirrie deposit is by far the largest, although the Lake Way deposit is also significant. There are many low-grade deposits, including Thatcher Soak, Lake Mason, Lake Raeside, Lake Maitland, Lake Austin, and Hinkler Well–Centipede.

Disseminated magmatic, pegmatitic and contact deposits in igneous and metamorphic rocks

The deposits in this group are associated with granite, migmatite, syenite, pegmatite, and carbonatite. At Rossing in Namibia the uranium is associated with pegmatitic granite and alaskite that intrude thick geosynclinal sequences; the country rock (now migmatite) appears to have been saturated and partly replaced by granitising fluids along shears, fractures, joints, and bedding planes. The uraniferous zones in the pegmatitic granite and alaskite are often red from the abundant K-feldspar and hematite. At Bancroft in Ontario, the uranium occurs in pegmatitic granite and syenite dykes.

Alkaline igneous complexes that intrude Precambrian shield areas commonly host large uranium deposits, as at Pocos de Caldas in Brazil (OECD-NEA & IAEA, 1980). Nepheline syenite is the dominant rock type and the mineralisation is concentrated in late-stage hydrothermal veins.

Deposits in this category make up a large proportion of the world's uranium resources. Major deposits include Rossing, Bancroft, Pocos de Caldas, and Ross-Adams (Prince of Wales Island, Alaska). Palabora in South Africa has produced uranium as a by-product of copper mining over many years.

Only a very minor proportion of Australian uranium resources fall into this category. The largest was Mary Kathleen, which has now been mined out. There are several small deposits in the Eastern Creek Volcanics north of Mount Isa, the largest of these being Valhalla, Skal, and Anderson's Lode. In the Olary Province (SA) there are several small deposits — Radium Hill, Crocker Well, and Mount Victoria. Further small deposits occur within the Mount Painter Complex (SA), including Mount Gee, Armchair, Streitberg, Radium Ridge, and Hodgkinson's.

The Mary Kathleen deposit occurred in Middle Proterozoic metasediments near a granite contact. It is assigned to this category, although it had some features of vein deposits.

At Crocker Well, thorian brannerite occurs in fractures and breccia zones in sodic granite, trondhjemite, and sodic alaskite. The Radium Hill orebodies are in steeply dipping shear zones in Proterozoic paragneiss and amphibolite. At Mount Victoria, the mineralisation occupies a system of fractures in migmatitic granite and gneiss.

The Mount Painter deposits are in granitic and hematitic breccia enclosed in metasediments and basement granite.

In the Gascoyne Block, alaskite and pegmatite which intrude the Morrissey Metamorphic Suite (Early Proterozoic) contain zones of low-grade uraninite mineralisation (Mortimer Hills).

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

Vein deposits

In the vein deposits, uranium minerals fill cracks, fissures, pore spaces, breccias, and stockworks. They range from massive veins of pitchblende (as at Jachymov in Czechoslovakia and Port Radium in Canada) to the narrow pitchblende-filled cracks, faults, and fissures in some orebodies in France and Australia.

The vein deposits contain only a small proportion of the world's uranium resources. Those in France, Spain, and Portugal are related to Hercynian leucogranites. At the Schwarzwalder deposits in Colorado, the fractures and veins cut Precambrian fine-grained biotitic schist. Vein deposits generally range in grade from 0.1–2% U, and in size up to 20 000 t contained U.

In Australia, vein deposits are quantitatively very minor. Maureen and Ben Lomond in the Georgetown–Townsville uranium field are the more significant deposits of this type. Many smaller vein deposits and prospects occur in various geological settings, including Early Proterozoic rocks of the Pine Creek Geosyncline, Proterozoic metamorphics near Port Lincoln, in the Mount Lofty Ranges, and in the Peake and Denison Ranges (all in SA), and Palaeozoic granites of the Lachlan and New England Fold Belts.

In the Georgetown–Townsville uranium field, several vein-type deposits containing uranium-fluorine-molybdenum mineralisation are related to late Palaeozoic acid volcanics. The volcanic complexes and related intrusions are preserved in fault-bounded cauldron subsidence areas. Mineralisation is hydrothermal and the deposits 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.

Quartz-pebble conglomerate deposits

Detrital uranium occurs in some Archaean–Early Proterozoic quartz-pebble conglomerates that unconformably overlie granitic and metamorphic basement. These deposits are restricted to a specific period of geological time: only conglomerates deposited in the time range 2800–2000 Ma contain uraninite (Skinner, 1975), and the largest known conglomerate-uranium deposits are in the age range 2800–2300 Ma. Fluvial transport of detrital uraninite was possible at the time because of the anoxic atmosphere (Roscoe, 1975; Robertson, 1975; Myers, 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 at the base of flat-lying Archaean–Proterozoic basin sequences and usually crop out around the edges of the basins. The conglomerates are highly pyritic and the pebbles 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. In deposits mined exclusively for uranium,

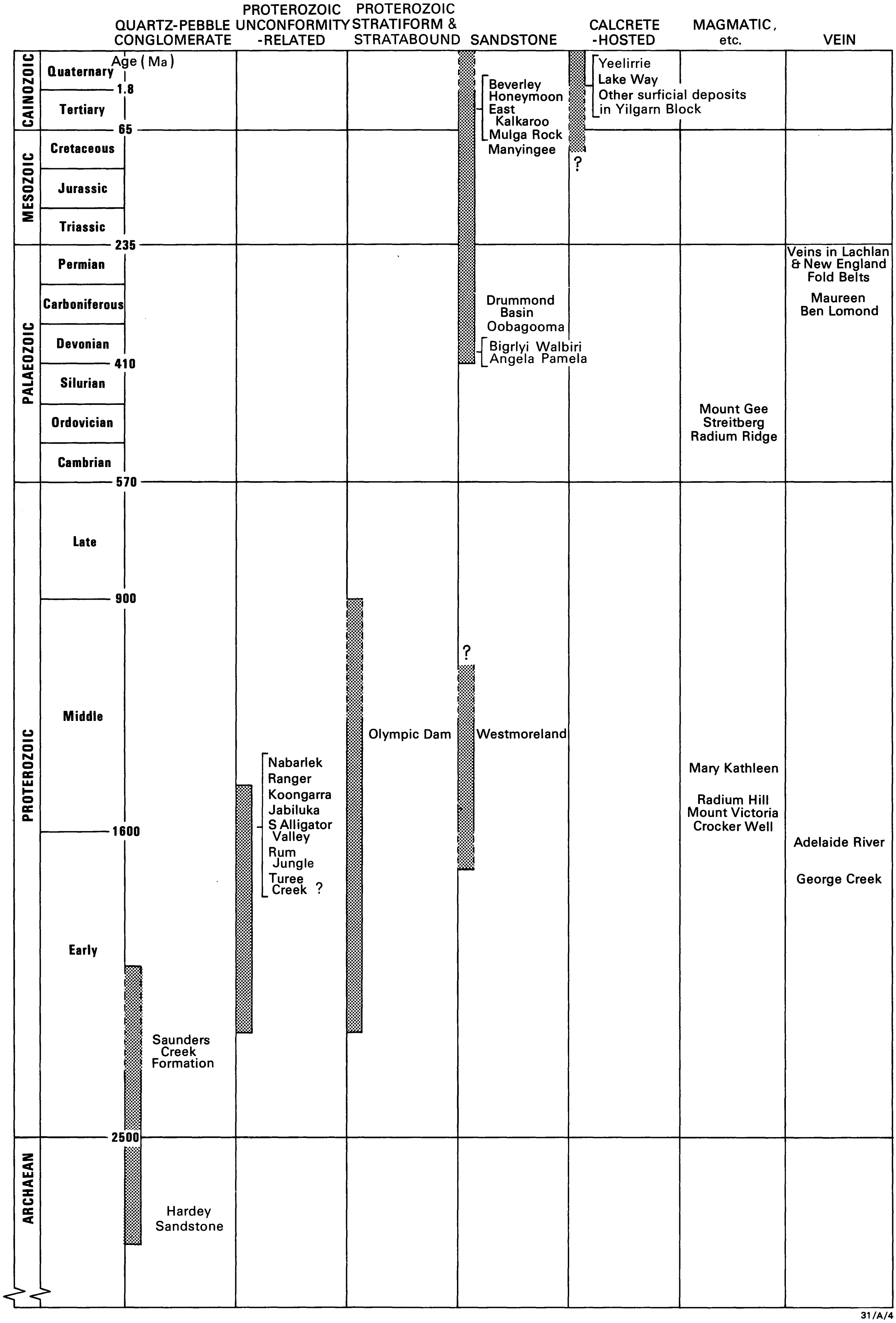

Fig. 4. Ages of Australian uranium deposits, and age-ranges (vertical bars) of the major types of deposits worldwide. For sandstone-type deposits the ages shown are those of the host rocks; for the other deposits the ages include the oldest mineralisation, which is known at some deposits to have been subsequently remobilised.

average grades range as high as 0.13% U. Individual deposits range in size from 5000–150 000 t contained U. Major examples are the Elliot Lake deposits in Canada and the Witwatersrand gold-uranium deposits in South Africa.

No such economic deposits are known in Australia, although quartz-pebble conglomerate containing low-grade uraninite mineralisation exists in several Archaean–Early Proterozoic basins in Western Australia. In the Hamersley Basin, WA, several zones of low-grade mineralisation occur in Archaean quartz-pebble conglomerate beds (Hardey Sandstone) at three places west of Nullagine — Bonnie Creek, Warralong Creek, and Croydon (Carter & Gee, in preparation; Hickman, 1983). Low-grade mineralisation also occurs 35 km northeast of Halls Creek, WA, in quartz-pebble conglomerate of the Archaean or Early Proterozoic Saunders Creek Formation.

Several areas of low-grade thorium-uranium mineralisation have been recorded in Middle Proterozoic quartz-pebble conglomerate in the Kimberley Basin; these are much younger than the economic conglomerate uranium deposits.

Other types

Uranium commonly occurs at concentrations of 100 to 150 ppm in marine phosphorite. Phosphorites are found in every continent, and major deposits in Morocco, the Middle East, and USA (Florida, Idaho, Utah, Wyoming) are mined for phosphate. Where phosphoric acid is produced, uranium is, in some instances, extracted as a by-product. The Cambrian phosphorite near Duchess in northwest Queensland has so far been mined for phosphate only — the contained uranium, generally less than 100 ppm U, is not extracted.

Marine carbonaceous black shale may contain uranium at concentrations of up to 300 ppm. Older marine black shales have higher concentrations than younger ones. The highest grades are in the Cambrian Kolm Shale at Randstad, Sweden, which averages 300 ppm U over large areas. In Spain, Cambrian black shales contain 60 ppm U; in Tennessee, the Devonian–Mississippian Chattanooga Shale contains 70 ppm U, and in South Africa, Permian black shale of the Karoo Basin contains up to 30 ppm U over large areas. Mesozoic black shales in the USA contain very low grades (Finch & others, 1982). In Australia, no potentially commercial concentration of uranium in black shale is known, although low concentrations (up to 70 ppm U) are widespread in the oil shale unit of the Cretaceous Toolebuc Formation in northwest Queensland.

Distribution through geological time

Uranium deposits have been formed in many geological environments. However, in most instances the uranium was deposited from either surface water or groundwater. With the exception of magmatic and vein-type deposits, the deposits in the various categories were formed in particular periods of geological time (Fig. 4). These geological time limits were determined by the physical and chemical environments that existed at those times (Robertson & others, 1978; Ferguson, 1984b).

The quartz-pebble conglomerate uranium deposits formed in the time-range 2800–2000 Ma (Skinner, 1975), because of the prevailing anoxic atmosphere in the Archaean and Early Proterozoic.

The unconformity-related deposits occur in Early and Middle Proterozoic sequences, in the time-range 2200–1400 Ma. During this period the atmosphere was gradually evolving and the oxygen-content increasing. The hydrosphere was sufficiently oxidising for uranium to be transported as the uranyl ion at or near the surface, but it has been suggested that reducing conditions prevailed at shallow depths (Ferguson, 1984). The uranium was precipitated as UO_2 from meteoric waters in suitable traps, largely developed during previous periods of prolonged erosion. The traps may have been active during the early sedimentation of the Middle Proterozoic cover rocks. Rapid burial by impermeable sediments preserved the uranium deposit from subsequent weathering and transport. In the post-1400 Ma period, the atmosphere was oxidising; thus, reducing conditions in groundwater would generally have been inadequate to precipitate uranium on any large scale, other than in restricted continental sandstone environments (Ferguson, 1984b).

Large stratiform and stratabound deposits, unrelated to unconformities, occur in Early and Middle Proterozoic sedimentary rocks.

Since the Silurian, reducing conditions have been localised by the anaerobic decomposition of extensive organic matter in continental sandstone. This has resulted in the deposition of uranium transported by surface and ground water in the oxidising atmosphere that has existed since the Early Proterozoic.

In Australia, the sandstone-type uranium deposits, with the exception of the Westmoreland deposits, are in sedimentary rocks which range in age from Late Devonian to Tertiary. The sandstone-type deposits in the Westmoreland area are exceptional as they occur in Middle Proterozoic strata; it has been proposed (Schindlmayr & Beerbaum, 1985) 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 circulating groundwater and deposited in the calcrete-layers in an oxidising environment.

The disseminated magmatic, pegmatitic, and contact deposits in igneous and metamorphic rocks, and the vein-type deposits, are not confined to any particular period of geological time: they occur in rocks ranging in age from Early Proterozoic to Late Palaeozoic.

Instead of emphasising the time-bound nature of various types of uranium deposits, Toens & Andrews-Speed (1984) consider that it is more important to consider the time-bound nature of different uranium-mineralising processes. Many deposits are the result of a series of mineralising steps which occurred over hundreds of millions of years. Toens & Andrews-Speed (1984) have identified five periods in the evolution of uranium mineralisation processes, related to the nature of tectonic activity during evolution of the crust and to the increase in oxygen levels during evolution of the atmosphere.

IDENTIFIED RESOURCES

In 1965 the OECD Nuclear Energy Agency began compiling information on uranium resources and demand for the WOCA countries. From 1967 the work was continued jointly with the International Atomic Energy Agency (IAEA). The two agencies have published this information periodically in a report, 'Uranium — Resources, Production and Demand', of which the 1986 edition is the eleventh (OECD-NEA & IAEA, 1986). The OECD-NEA currently consists of all the European members of OECD, plus Australia, Canada, Japan, and the USA. The report is prepared from data provided by national authorities in response to questionnaires distributed by the NEA/IAEA Uranium Group. It reviews the uranium supply position in the WOCA countries by presenting data on exploration activities, uranium resources, past and present production, and plans for future expansion, and compares these data with possible future requirements.

The resource estimates are divided into separate categories reflecting different levels of confidence. The resources are further separated into categories based on the cost of production.

The various resource categories are defined by NEA/IAEA as follows:

— **Reasonably Assured Resources (RAR)** refers to uranium that occurs in known mineral deposits of such size, grade, and configuration that it could be recovered within the given production cost ranges, with currently proven mining and processing technology. Estimates of tonnage and grade are based on specific sample data and measurements of the deposits and on knowledge of deposit characteristics. RAR have a high assurance of existence and in the cost category below \$80/kg U are generally considered as *reserves*.

— **Estimated Additional Resources — Category 1 (EAR–I)** refers to uranium in addition to RAR that is expected to occur, mostly on the basis of direct geological evidence, in extensions of well-explored deposits, and in deposits in which geological continuity has been established, but where specific data and measurements of the deposits and knowledge of the deposits' characteristics are considered to be inadequate to classify the resource as RAR. Such deposits can be delineated, and the uranium subsequently recovered, all within the given cost ranges. Estimates of tonnage and grade are based on such sampling as is available and on knowledge of the deposit characteristics as determined in the best known parts of the deposit or in similar deposits. Less reliance can be placed on the estimates in this category than on those for RAR.

— **Estimated Additional Resources — Category II (EAR–II)** refers to uranium in addition to EAR–I that is expected to occur in deposits believed to exist in well-defined geological trends or areas of mineralisation with known deposits. Such deposits can be discovered, delineated, and the uranium subsequently recovered, all within the given cost ranges. Estimates of tonnage and grade are based primarily on knowledge of deposit characteristics in known deposits within the respective trends or areas and on such sampling, geological, geophysical, or geochemical evidence as may be available. Less reliance can be placed on the estimates in this category than on those for EAR–I.

— **Speculative Resources (SR)** refers to uranium, in addition to EAR–II, that is thought to exist mostly on the basis of indirect evidence and geological extrapolation, in deposits discoverable with existing exploration techniques. The location of deposits envisaged in this category could generally be specified only as being somewhere within a given region or geological trend. As the term implies, the existence and size of such resources are highly speculative.

The resource categories are further subdivided on the cost of production into: (1) less than \$80/kg U, (2) \$80–\$130/kg U, and (3) \$130–\$260/kg U. The costs are expressed in US dollars.

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

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

Sunk costs are not normally taken into consideration.

It has been necessary from time to time during the past twenty years to alter the NEA/IAEA cost categories to accommodate increases in costs.

The resource estimates are expressed as quantities of uranium recoverable after allowing for ore dilution and mining and milling losses.

The NEA/IAEA classification, which has been adopted internationally for uranium resources, can be broadly equated with the resource classification system used by BMR for other minerals. RAR at less than US\$80/kg U approximates recoverable Economic Demonstrated Resources; RAR in the US\$80–130/kg U category approximates recoverable Subeconomic Demonstrated Resources; EAR–1 is equivalent to recoverable Inferred Resources. The NEA/IAEA classification differs from the BMR system in that it quantifies the cost of production of economic and subeconomic resources.

Resource estimates within the various categories change with shifts in economic conditions and with progress in exploration and technology. Local production costs may vary as a result of inflation or variations in exchange rates and hence the cost of recovering uranium in certain deposits crosses the boundary between two cost classifications and the estimates have to be reclassified. As exploration proceeds there is a movement of resources from EAR–Category 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. It is not uncommon for a particular deposit to contain resources in a number of these resource categories.

The Australian estimates are prepared from basic exploration data provided by companies in accordance with the Atomic Energy Act 1953. The practice is for BMR to prepare a draft report for each deposit, detailing its estimate of the in-situ resource, the parameters on which the estimate is based, and an explanation of any differences from company estimates. The draft report is then discussed with technical officers of the company. From the estimates of in-situ resources, estimates of recoverable uranium are prepared, making allowance for mining and milling losses, and a final report is prepared. These estimates are regarded as 'commercial-in-confidence' and are never published. They are aggregated as national totals for the various resource categories. The relative order of importance of the different types of deposits can be gained from figures published by companies (Table 5).

The national resource totals are published annually by BMR in the Uranium chapter of the *Australian Mineral Industry Annual Review* (they are first made available each year in a press release, and later in a preprint of the Uranium chapter).

As at 1 January 1986, Australia had 29% of the WOCA countries' low-cost RAR and 28% of the WOCA countries' low-cost EAR–Category I (Table 6).

Table 6. Recoverable uranium resources, WOCA countries, 1 January 1986

	Cost range: up to US\$80/kg U (US\$30/lb U_3O_8)		*Cost range: US\$80–130/kg U (US\$30–50/lb U_3O_8)*	
	Reasonably Assured Resources	*Estimated Additional Resources — Category I*	*Reasonably Assured Resources*	*Estimated Additional Resources — Category I*
Algeria(a)	23 400	—	—	—
Argentina	15 380	7 700	3 550	200
Australia(d)	465 000	256 000	56 000	127 000
Brazil(b)	130 620	73 910	—	—
Canada	160 000	103 000	72 000'	100 000
France	52 213	27 218	10 675	17 586
Gabon	16 730	1 300	4 650	8 300
India	35 130	2 120	10 960	14 490
Namibia	104 000	30 000	16 000	23 000
Niger	180 000	283 600	2 200	16 700
South Africa	256 600	97 500	102 100	27 100
Sweden	2 000	2 300	37 000	44 000
USA	133 000	—	280 000	—
Others(c)	56 560	22 280	65 020	35 160
Total	1 630 633	906 928	660 155	413 536
(rounded)	(1 631 000)	(907 000)	(660 000)	(414 000)

Source: OECD-NEA & IAEA (1986) and OECD-NEA (1986), except for Australia which is Bureau of Mineral Resources (1986).
(a) National total, published as mineable resources, has been adjusted for milling losses assumed to be 10%.
(b) National total, published as in-situ resources, has been adjusted to allow for mining and milling losses assumed to be 20%.
(c) Austria, Central African Republic, Chile, Denmark, Finland, Federal Republic of Germany, Greece, Italy, Japan, Republic of Korea, Mexico, Peru, Portugal, Somalia, Spain, Turkey, Zaire. Appropriate adjustments have been made, according to whether national totals are stated as 'mineable' or 'in situ'.
(d) As at 31 December 1986, Australian resources in the cost range up to US\$80/kg U were reduced by 3000 t U (RAR) and increased by 1000 t (EAR).

POTENTIAL FOR FURTHER DISCOVERIES

BMR estimated in 1984 that there is a 75% probability that the undiscovered resources in Australia amount to more than 2 600 000 t U, and a 50% probability that they may exceed 3 900 000 t U.

The potential for finding more **Proterozoic unconformity-related** uranium deposits in the Alligator Rivers uranium field is very high. This field covers 25 000 km² and comprises Archaean to Early Proterozoic complexes of granitoid rock, gneiss, and migmatite mantled and surrounded by Early Proterozoic sedimentary and metamorphic strata which are overlain to the east and south by Middle Proterozoic sandstone and volcanics. Mesozoic sandstone and Cainozoic sand and alluvium cover much of the central and northern parts of the region. The known uranium deposits are in the Early Proterozoic metamorphics. Because much of the potential host rock is covered by younger sandstone, sand, and alluvium, the relatively limited exploration to date has probably located only a fraction of the uranium resources in the region. Moreover, there is a possibility of further discoveries of this type of deposit in other parts of the Pine Creek Geosyncline and also in Western Australia extending from the Turee Creek area, beyond the Sylvania Dome, to the East Pilbara region, where Archaean basement, Early Proterozoic metasediments, and a Middle Proterozoic unconformity are present. Other prospective areas may be the Killi Killi Hills area (WA), the Halls Creek area (WA), the Tennant Creek area (NT), and the southwest of Eyre Peninsula (SA).

A major portion of Australia's known resources occur in the Olympic Dam **Proterozoic stratabound** deposit on the Stuart Shelf in South Australia. The top of the deposit is 350 m below the surface. Mineralisation has been found elsewhere on the Stuart Shelf and, considering the thickness of barren cover in the region and the relatively limited exploration to date, there are good prospects for discovering other deposits.

There is also potential for further significant discoveries of **sandstone-type** deposits in Australia. Many of the known deposits are proximal to basement rocks containing uranium deposits or anomalous uranium concentrations. Typical are the deposits in Tertiary sediments of the Frome Embayment, which is flanked by Proterozoic basement containing the Mount Painter and Olary uranium fields. There are sandstone uranium deposits in Cretaceous sandstone of the Carnarvon Basin and Tertiary sediments of the Officer Basin, where these basins are adjacent to the Western Australian Precambrian shield. Other deposits are known in the Devonian–Carboniferous sandstones of the Ngalia, Amadeus, and Canning Basins and in Middle Proterozoic sandstone along the southeastern margin of the McArthur Basin.

Low-grade uranium mineralisation has been recorded in Eocene sediments north of the Eyre Peninsula, SA, along extensive ancient stream channels that drained the Precambrian basement of the Gawler Domain. Uranium mineralisation is also known in Carboniferous sedimentary rocks in the Drummond Basin, Qld.

The results of past exploration indicate further sandstone uranium discoveries can be expected in younger sedimentary basins near Precambrian areas such as the Pine Creek Geosyncline, Mount Isa Block, Arunta Block, and Musgrave Block. Most of the uranium deposits of the sandstone type discovered to date in Australia do not crop out, and, in the light of the relatively limited exploration so far, further significant discoveries are likely.

According to Gaskin & others (1981) there are three main regions of calcrete formation in Australia, totalling about 2 000 000 km². The known significant calcrete-type uranium deposits are confined to the western region, comprising the northern half of the Archaean Yilgarn block and the Early Proterozoic basins to the north (Fig. 15). This region has been extensively explored for these relatively shallow targets and hence the potential for discovering more **calcrete-type** uranium deposits of comparable grade to Yeelirrie is limited. However, there is still considerable potential for large very-low-grade calcrete-type uranium deposits.

The eastern areas of calcrete formation extend into the southern half of the Northern Territory and the northern part of South Australia. Provided that climatic conditions in the past were favourable for precipitation of economic concentrations of carnotite, some potential may exist in regions of Archaean and Early Proterozoic basement rocks.

There is potential for further discoveries of **disseminated magmatic, pegmatitic and contact** deposits, although in some areas the potential has been reduced by intensive exploration, as around Mary Kathleen and in the Olary mineral field.

Vein deposits constitute only a small proportion of uranium resources in Australia and elsewhere in the world. Nevertheless, most of the orogenic provinces in Australia have potential for this type of deposit. There are prospects of further discoveries of the Ben Lomond or Maureen type in the Georgetown–Townsville field and in other areas in which vein types have been found. However, they are unlikely to form major additions to resources.

Uranium deposits in Archaean–Early Proterozoic **quartz-pebble conglomerate** account for a major proportion of world resources, but have not been found to date in Australia despite more than 40 exploration programs over the last 30 years. Pyritic quartz-pebble conglomerate occurs in several Precambrian sedimentary sequences in Western Australia. However, only those occurrences at higher stratigraphic levels in the Pilbara Block and at lowermost stratigraphic levels of the superposed Hamersley Basin have provided any encouragement. Most exploration has been directed at the Hardey Sandstone at the base of the Hamersley Basin. Several zones of low-grade uranium mineralisation have been intersected (Carter & Gee, in preparation). These authors stated that the potential source rocks of uranium mineralisation were covered by basalt during early stages in the erosion of the basement and this may have reduced the quantity of uraninite available and hence may have decreased the possibility of significant uranium grades in the quartz-pebble conglomerate. However, Carter (1981), in reviewing the exploration and drilling carried out in the Hardey Sandstone, stated that a large proportion of the conglomerate unit had not been tested and it may still be possibile to locate higher-grade lenses.

In the Witwatersrand and at Elliot Lake the mineralised conglomerates commonly were deposited as alluvial fans. Such fans are difficult to locate as they are concealed by younger flat-lying Proterozoic strata; outcrops of these mineralised fans are usually restricted to small areas where the fans originally entered the basin and are hard to find.

In view of the large areas of Archaean to Early Proterozoic outcrop in Australia, the absence of uranium deposits in quartz-pebble conglomerate seems anomalous. One possible reason is that a large proportion of the Archaean–Early Proterozoic outcrop is now in arid climatic regions characterised by deep weathering and near-surface leaching of uranium minerals, rendering surficial radiometric exploration techniques ineffective.

DESCRIPTIONS OF THE DEPOSITS

PROTEROZOIC UNCONFORMITY-RELATED DEPOSITS

Alligator Rivers uranium field

This field is in the Pine Creek Geosyncline (Figs. 5 and 6) 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 area around each of these deposits was excised from the park. 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 that showed probable Archaean basement overlain by Early Proterozoic strata and Middle Proterozoic sandstone in the area now known as the Alligator Rivers uranium field. Similarities with the Archaean–Early Proterozoic setting at Rum Jungle and the presence of uranium-bearing Middle Proterozoic sandstone in the Westmoreland area attracted uranium and base-metal explorers to the Alligator Rivers region.

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 northeastern part of the Pine Creek Geosyncline (Needham & Stuart-Smith, 1980). In this area the regional metamorphic grade and degree of deformation are markedly greater than elsewhere in the geosyncline. In the western part of the field, Early Proterozoic metasediments overlie and grade into Archaean–Early Proterozoic granitoid of the Nanambu Complex. In the northeast the metasediments also surround granite and tonalite intrusives and migmatite of the Early Proterozoic Nimbuwah Complex. All of these rocks were intensely folded and metamorphosed between 1870 and 1800 Ma (Needham, 1982b). Over most of the field the metamorphism reached amphibolite grade and it reached granulite grade in parts of the Nimbuwah Complex. Prior to metamorphism, the Early Proterozoic sequence was intruded by the Zamu Dolerite; after the metamorphism it was intruded again, by granite and the Oenpelli Dolerite, at 1690 Ma (Page & others, 1980).

The Early Proterozoic sequence is unconformably overlain by Middle Proterozoic Kombolgie Formation sandstone of the Katherine River Group.

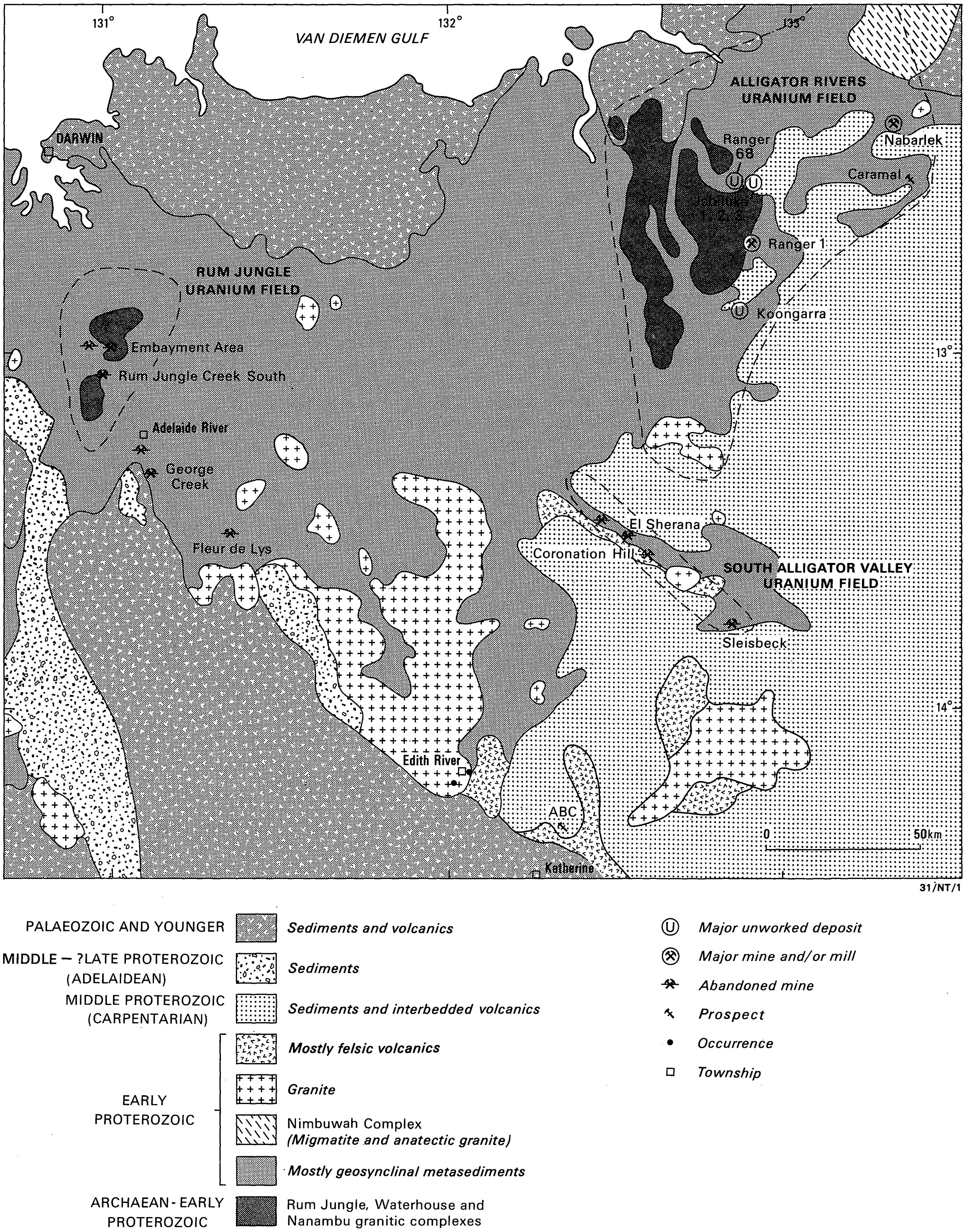

Fig. 5. Generalised regional geology, Pine Creek Geosyncline, showing uranium fields and localities.

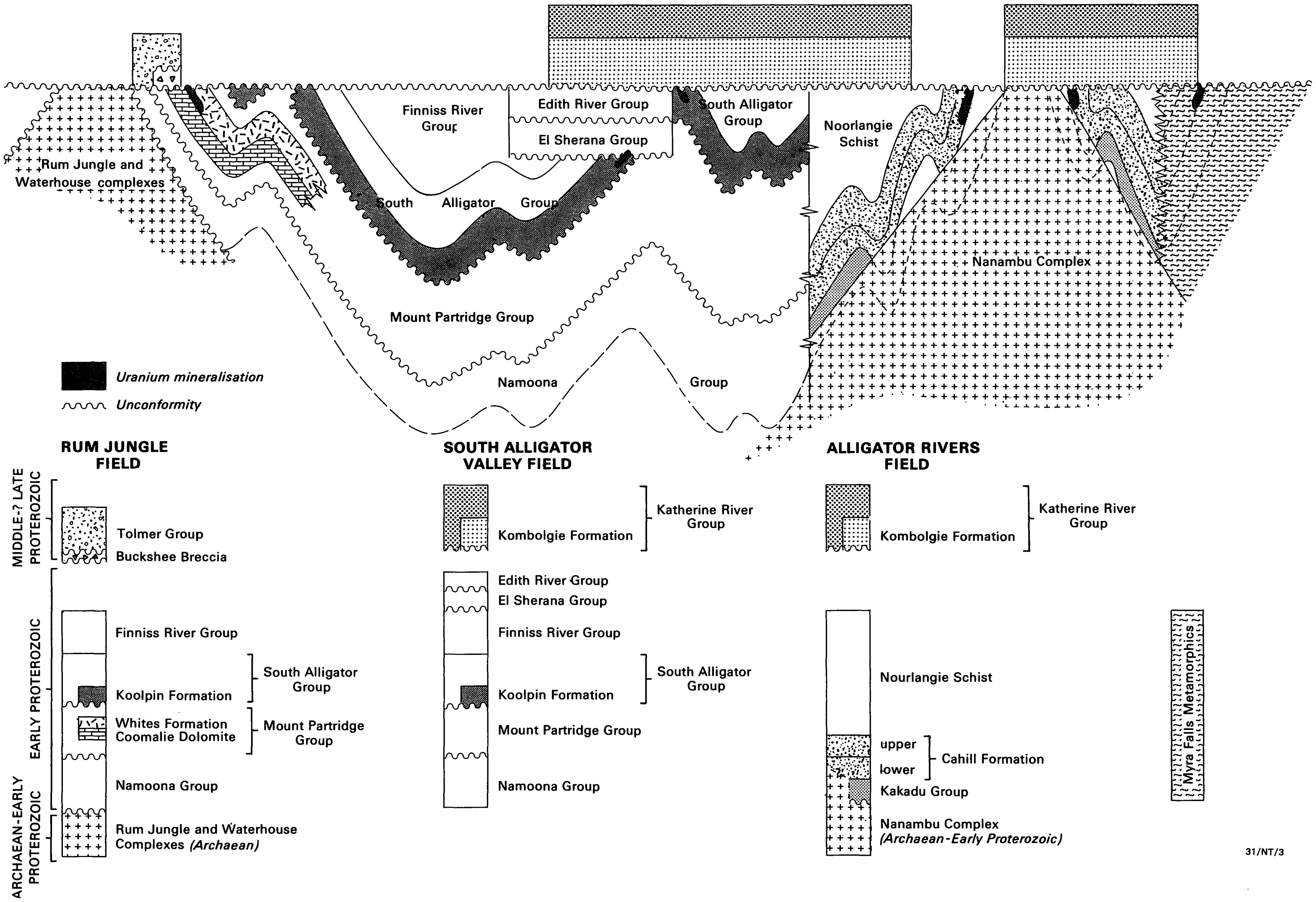

Fig. 6. Schematic diagram of relationships between uranium mineralisation, favourable host rocks, and the Early/Middle Proterozoic unconformity in the Pine Creek Geosyncline. The diagram does not fully represent the stratigraphy, but is an attempt to show the relationships between units significant in describing the uranium mineralisation. Igneous rocks other than basement units have been omitted.

The Jabiluka, Ranger 1, and Koongarra deposits and most of the significant uranium prospects are in the lower member of the Early Proterozoic Cahill Formation around the Nanambu Complex (Needham & Stuart-Smith, 1980). The Nabarlek deposit is in the Myra Falls Metamorphics near the Nimbuwah Complex, in rocks that may be metamorphosed equivalents of the lower member of the Cahill Formation.

The uranium deposits post-date the regional metamorphism (which has been dated at 1870–1800 Ma), and isotopic dating of uraninite and galena indicates ages of mineralisation and remobilisation at 1600 Ma, 900 Ma, and 500 Ma (Ewers & others, 1984).

Ewers & others (1984) noted the following features common to the uranium deposits in the Alligator Rivers, Rum Jungle, and South Alligator River uranium fields:

- Stratabound ore zones
- Association with zones of brecciation or shearing
- Regional association of most of the mineralisation with carbonate rock, but an antipathetic relationship with carbonate in the ore zones
- Shallow depth
- Intense, pervasive chloritisation of ore zones, wall rocks, and Middle Proterozoic cover rocks
- Absence of extensive mineralisation in the cover rocks, despite the local abundance of chloritised zones
- Association with the Early/Middle Proterozoic unconformity, which approximates to the present-day land surface.
- High U/Th ratios
- The wide spread of apparent ages of mineralisation
- Proximity of the deposits to the overlying Middle Proterozoic cover rocks

In the Alligator Rivers and Rum Jungle fields, the proximity to the Archaean–Early Proterozoic complexes appears significant. There is also some suggestion that the grade of deposits in the Alligator Rivers field improves down-dip along the sub-Middle Proterozoic unconformity.

Different mechanisms have been proposed to explain the origin (including source, transport, and formation) of the deposits, and some of these models are outlined below:

- Crick & Muir (1980) proposed a sabkha environment in which uranium was enriched in evaporitic sediments, followed by expulsion of uranium-rich brines during diagenesis. The major phase of uranium concentration in deposits is postulated to have occurred during post-metamorphic replacement of evaporites by magnesite.
- From their work on Nabarlek and Jabiluka, Ypma & Fuzikawa (1980) concluded that uranium was transported in low-temperature, carbon-dioxide-rich meteoric waters along or close to the Early–Middle Proterozoic unconformity. Uranium was deposited at the confluence of the meteoric waters with hypersaline calcium-chloride brines, possibly involving reduction by methane.
- Gulson & Mizon (1980) concluded from their work on the Jabiluka deposits that uranium was transported as uranous complexes in brines.
- Ferguson & others (1980) and Ewers & others (1984) have postulated a supergene genetic model in which breccia ore zones were probably produced in carbonate-rich sequences during peneplanation of the Early Proterozoic strata and before the Middle Proterozoic cover rocks were deposited. Downward-percolating meteoric waters transporting uranyl complexes were met by reducing conditions in breccia zones where uranium oxide was precipitated.
- Needham & Stuart-Smith (1980) have proposed that the stratabound nature of the ore suggests that it formed partly syngenetically, but they also suggested that epigenetic processes appear essential for the development of such high-grade deposits.
- Binns, McAndrew, & Sunn (1980) postulated a hypogene source from their work on Jabiluka — possibly hydrothermal fluids which deposited uranium mineralisation in hydraulic fracture zones.
- Gustafson & Curtis (1983), from their work on Jabiluka, concluded that high-grade uranium ores were the product of a low-temperature 100–200°C hydrothermal system involving groundwater. This system was driven by a regional heating event also manifested by phonolite and/or diabase intrusions after the deposition of the Kombolgie Formation sandstone.

Ranger 1 deposits

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. 7) (Ryan, 1972). By the end of 1970 at least two viable orebodies — 1 and 3 — had been outlined by drilling of the more significant anomalies (Eupene, Fee, & Colville, 1975). Preliminary construction started in February 1979 and mining in August 1981.

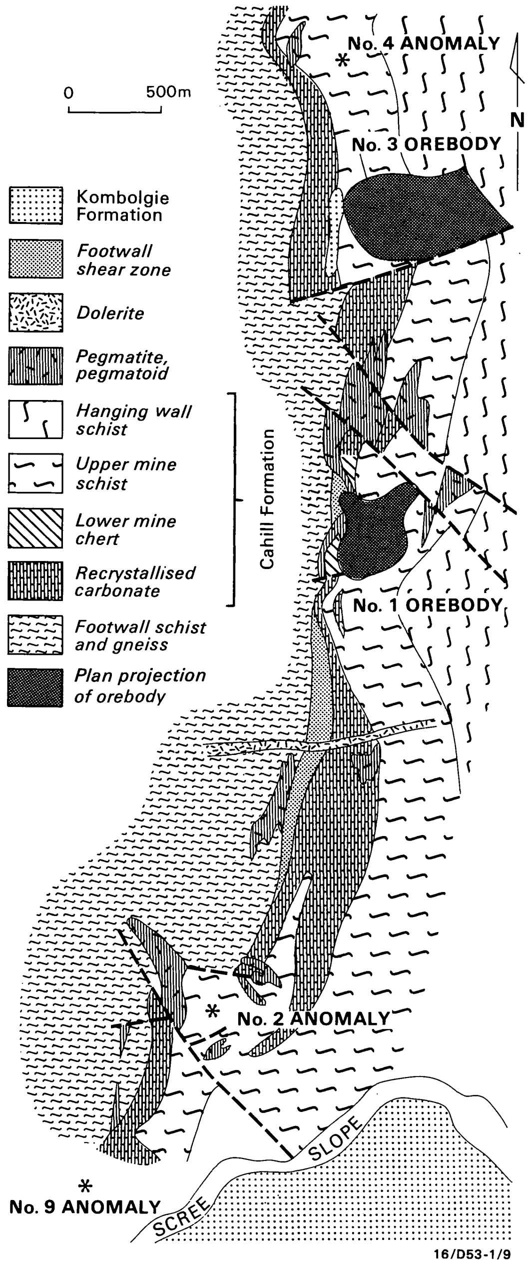

Fig. 7. Generalised solid geology (plan), Ranger 1 orebodies and prospects (from Needham, 1982a, after Eupene & others, 1975, and Hegge & others, 1980).

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. 8) 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.

No. 1 Orebody, No. 3 Orebody. No. 1 Orebody is 1500 m south of No. 3 Orebody. Most of the ore is in the Upper Mine Sequence, which is mainly chloritised biotite-quartz-feldspar schist and microgneiss with thin carbonaceous lenses. No. 1 Orebody extends roughly 500 m along strike and about 300 m across strike and is somewhat basin-shaped. It is broadly conformable with the host rocks, striking north-south, with an overall dip to the east (Fig. 8). More than half of the ore is contained in fresh, unweathered schist of the Upper Mine

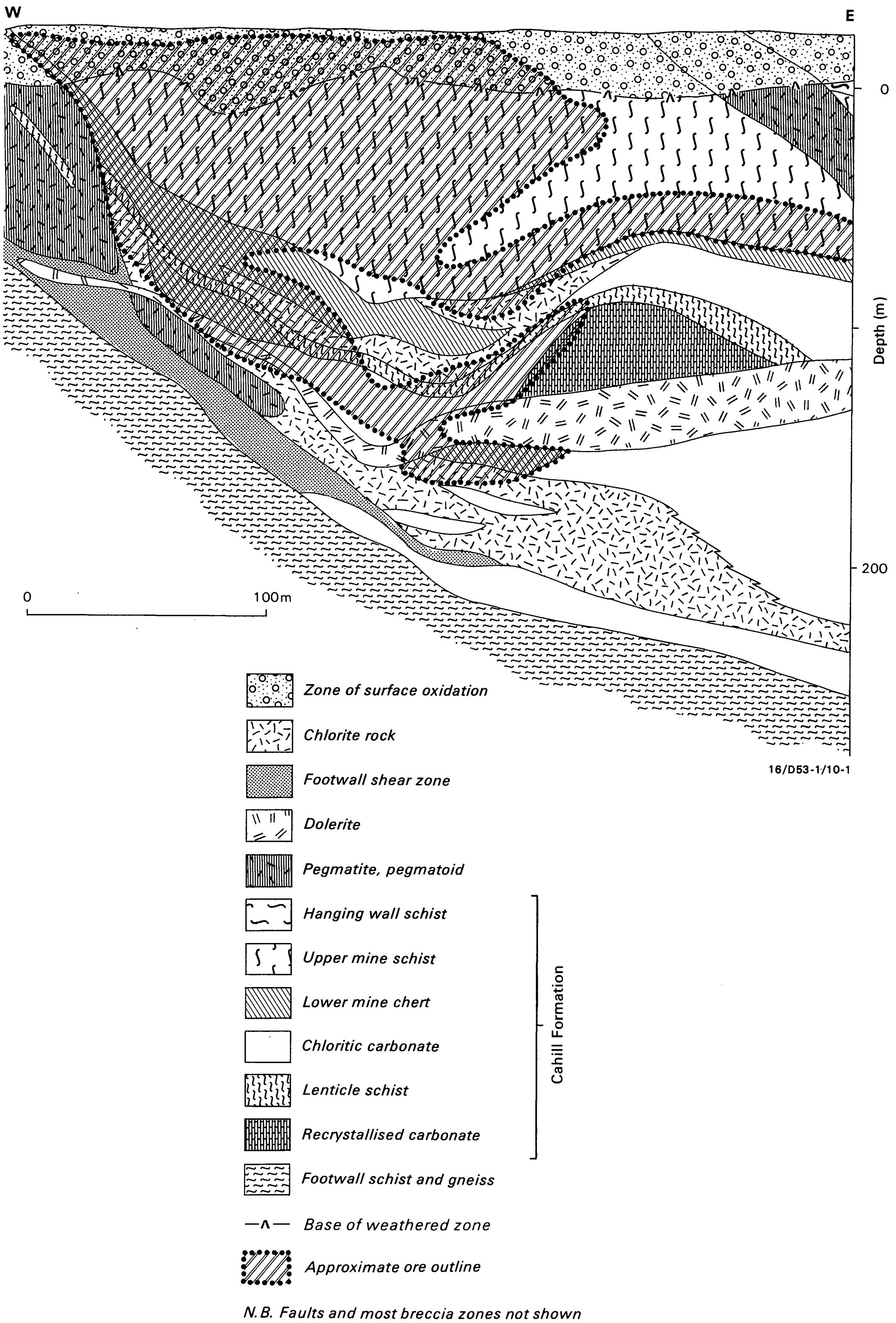

Fig. 8. Cross-section of No. 1 orebody at Ranger 1 (from Needham, 1982a, after Eupene & others, 1975, and Hegge & others, 1980).

Sequence (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. A large block of chloritised Kombolgie Formation sandstone occurs on the western side of No. 3 Orebody. A blind deposit occurs in the Lower Mine Sequence east of No. 3 Orebody, about 250 m below the surface.

Both the Upper and Lower Mine Sequences are severely brecciated in the ore zones and extensively intruded by chlorite veins, which carry most of the mineralisation (Hegge, Mosher, Eupene, & Anthony, 1980). A distinctive thin band with characteristic chlorite lenticles forms an important marker horizon (Eupene & others, 1975).

The primary ore consists of uraninite with minor brannerite and amorphous mixtures of uranium (pitchblende) with titania 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). Minor amounts of native gold are present.

Other prospects. Anomalies 2 and 9 of the Ranger 1 group are approximately 3 km south of the No. 1 Orebody (Fig. 6). Anomaly 2 was extensively auger and percussion drilled. Hegge & others (1980) stated that there was 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 northwest 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.

Nabarlek deposit

Queensland Mines Ltd discovered the Nabarlek deposit in 1970, and during 1970 and 1971, the orebody was delineated by costeaning and drilling. The deposit was mined and stockpiled for milling between May and October 1979. Production of yellowcake from the stockpiled ore commenced in June 1980.

The host rocks are the Myra Falls Metamorphics, which are thought to correlate in part with the Cahill Formation (Needham, 1982b). The orebody was 230 m long and thinly wedge-shaped in cross-section (Fig. 9) with a true thickness varying widely but averaging 10 m. It occupied a highly chloritised shear zone striking north-northwest and dipping at 30°–45° to the east, and consisted of two main high-grade lenses surrounded by a lower-grade envelope. 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 the Oenpelli Dolerite.

The mineralisation was in massive fine-grained dark-green chlorite-sericite-hematite rock, breccia, and altered schist (Anthony 1975; Ewers, Ferguson & Donnelly, 1983). Rock types in the immediate vicinity of the orebody are chlorite-, muscovite-, and sericite-rich schist. Below the orebody, at a vertical depth of 470 m, the metasediments are intruded by the Nabarlek Granite.

In the primary zone, the orebody contained irregular lenses of pure pitchblende with drill-core intersections of up to 1 m (Anthony, 1975). Ewers & others (1983) state 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.

According to Hills & Richards (1976) there is no indication of uranium mineralisation at Nabarlek that is older than 920

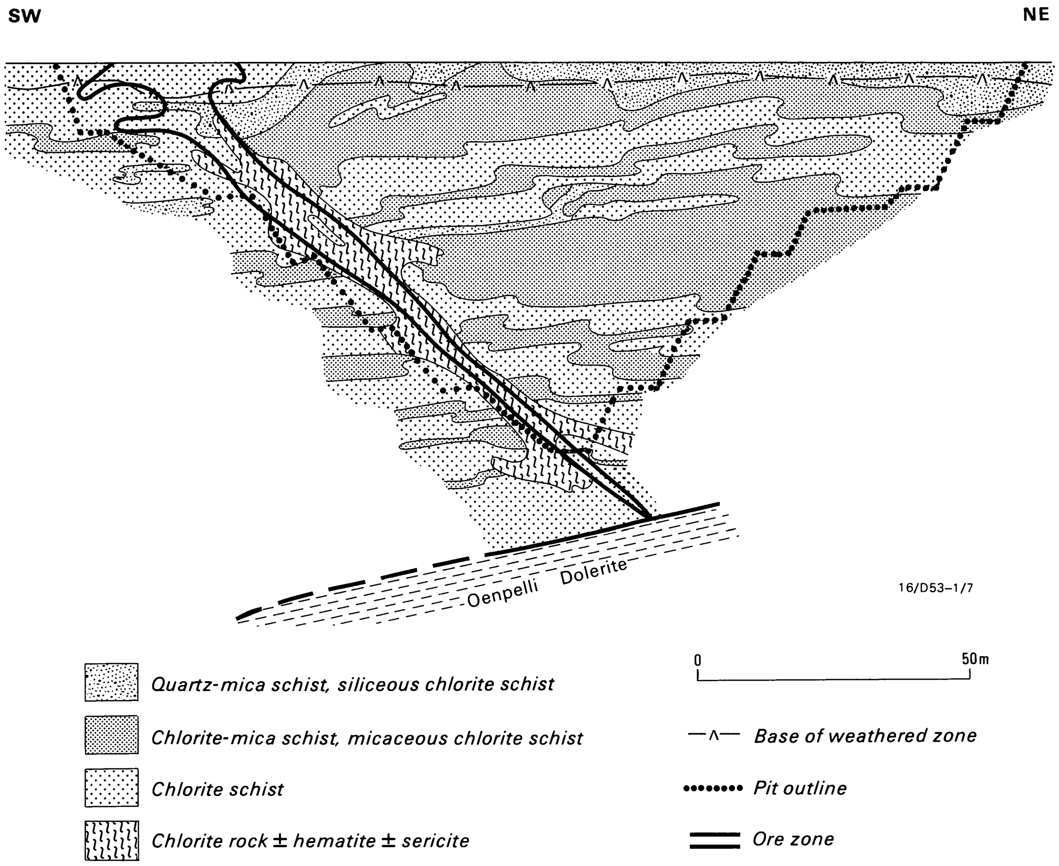

Fig. 9. Cross-section, southern end of Nabarlek orebody (from Needham, 1982c, modified from mine section 9553 and published by courtesy of Queensland Mines Ltd).

Ma. However, Ewers & others (1983) point out that widespread sericitisation at around 920 Ma may have erased evidence of an older uranium age.

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 Formation sandstone (Figs.10 and 11). The final EIS for development of the deposits was submitted in July 1979 (Pancontinental Mining Ltd, 1979).

Jabiluka 1 and 2 are in the lower member of the Cahill Formation, at the northeastern margin of the Nanambu Complex. Jabiluka 1 lies just west of a large outlier of the Kombolgie Formation, but Jabiluka 2, 300 m east of Jabiluka 1, is concealed by up to 200 m of Kombolgie Formation sandstone. A third deposit, Jabiluka 3, was indicated in one drillhole south of Jabiluka 1 (Hegge & others, 1980). Both Jabiluka 1 and 2 deposits occur within an open asymmetric flexure, striking east-southeast and dipping to the south.

The Jabiluka 1 deposit measures about 400 m in a northwesterly direction and 200 m in a northeastly direction (Hegge, 1977). It dips south at 15 to 30 degrees, and in the Main Mine Series the ore zone is up to 35 m thick. Jabiluka 2 deposit is still open to the south and east at depth. It extends for at least 1000 m in a west-northwest direction and at least 400 m north–south. The deposit dips south in a series of flexures at between 30 and 60 degrees. 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.

In the vicinity of the deposits, retrograde metamorphism resulted in chloritisation of biotite and garnet and sericitisation of feldspar, sillimanite, and cordierite.

Mineralisation consists of pitchblende as vein fillings, disseminated grains in chlorite gangue, and selvedges to chlorite veins or local replacement zones. Minor coffinite, brannerite, and rare thucholite are also present. Sulphides include pyrite with lesser chalcopyrite and galena. Major gangue minerals are chlorite, quartz, sericite, and graphite.

A gold deposit in the western part of Jabiluka 2 measures 300 x 150 m in plan. The gold is mainly in breccia zones of the Main Mine Series; the ore averages 2 m, and is up to 12 m, thick (Hegge, 1977).

Koongarra deposits

The No. 1 orebody at Koongarra (Figs. 12 and 13) 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 were delineated by drilling between 1970 and 1973.

A final Environmental Impact Statement for development and mining of the deposit was submitted in 1979 (Noranda Australia Ltd, 1979).

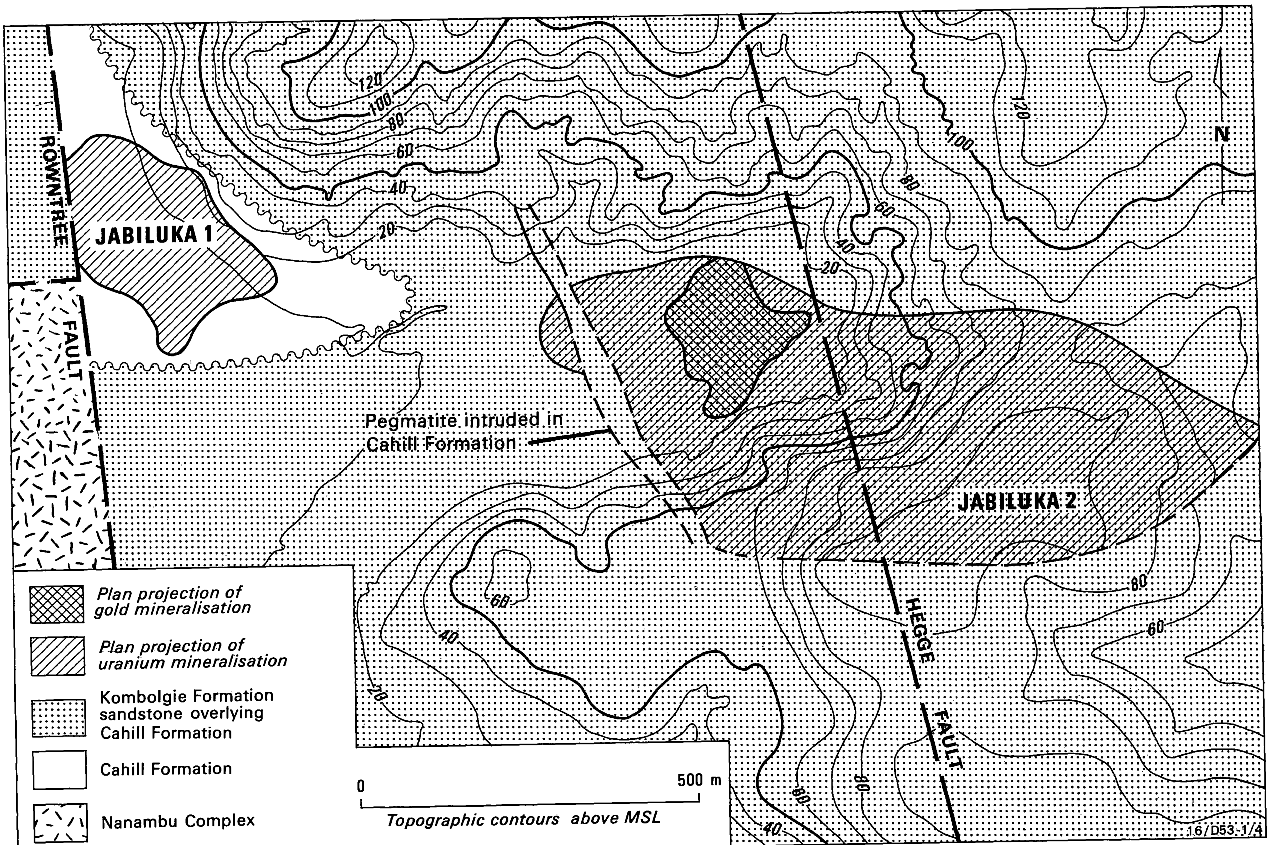

Fig. 10. Solid geology of Jabiluka 1 and 2 deposits (from Needham, 1982a, adapted from revised unpublished data by courtesy of Pancontinental Mining Ltd).

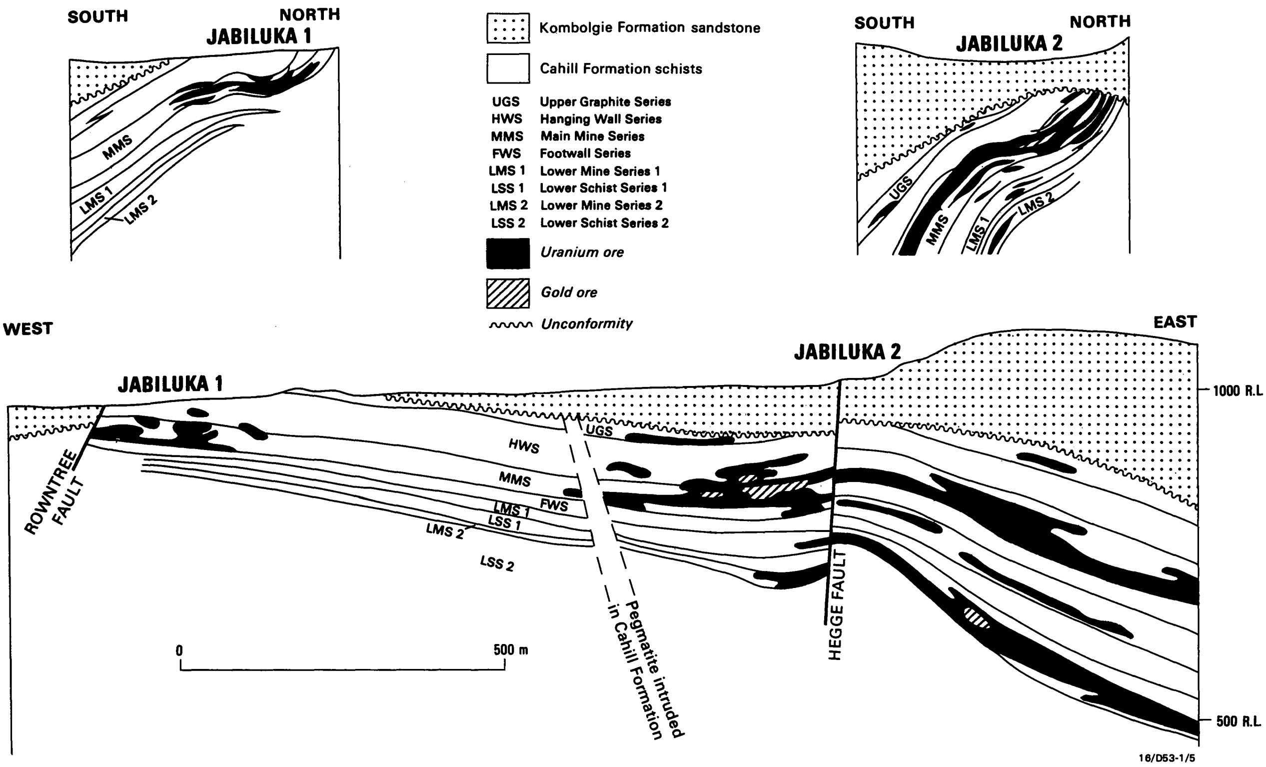

Fig. 11. Generalised long-section and cross-sections of Jabiluka 1 and 2 deposits (from Needham, 1982a, adapted from revised unpublished data by courtesy of Pancontinental Mining Ltd).

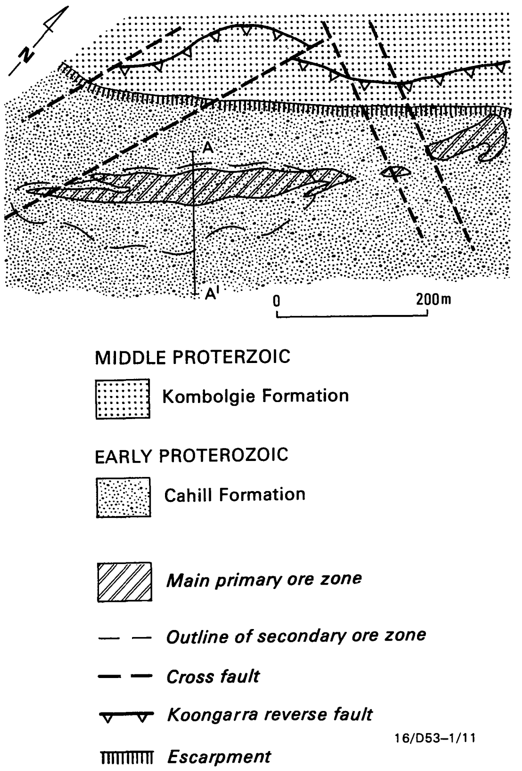

Fig. 12. Plan of Koongarra deposit (from Needham, 1982a, after Foy & Pedersen, 1975, and Hegge & others, 1980).

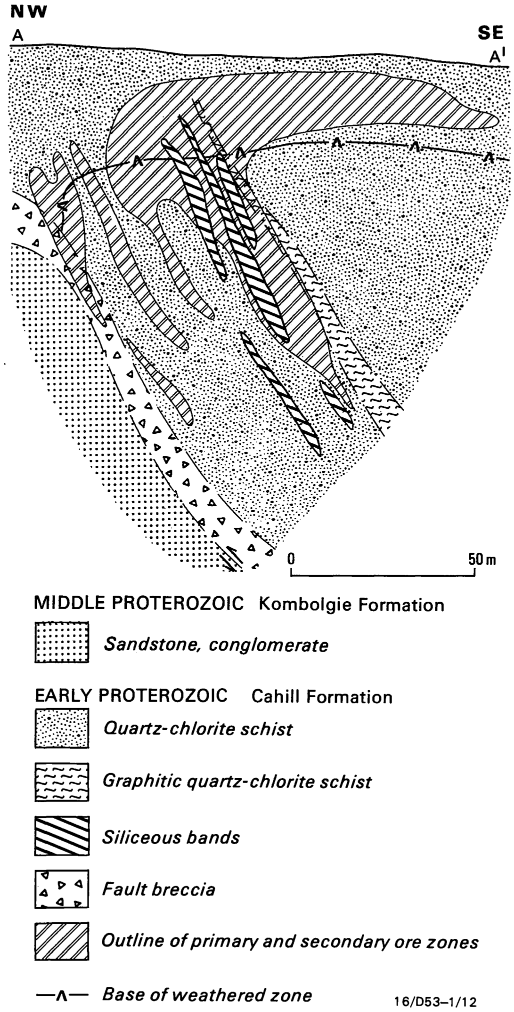

Fig. 13. Cross-section, Koongarra No. 1 orebody (from Needham, 1982a, after Foy & Pedersen, 1975, and Hegge & others, 1980).

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

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 southeast. The secondary mineralisation, in weathered schist above the No. 1 Orebody, comprises ore-grade material dispersed 80 m downslope to the southeast. The No. 2 Orebody is northeast of No. 1 Orebody and has a strike length of 100 m. Mineralisation occurs between 50 and 250 m below surface and does not extend into the weathered zone (Hegge & others, 1980; Snelling, 1980).

The Early Proterozoic sequence at the No. 1 Orebody is upfaulted against the Kombolgie Formation, 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. Pyrite and traces of chalcopyrite and galena are often present in the high-grade ore, and gold has been detected in assays. The main gangue is quartz, chlorite, and mica. A detailed description of the ore mineralogy is given by Snelling (1980).

Other deposits and prospects

The **Ranger 68** deposit, 5 km west of Jabiluka 1, was located by scout drilling along the favourable Cahill Formation/Nanambu Complex contact (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. The sooty and colloform pitchblende 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, but the boundaries of the mineralised zone had not been defined. Some of the better intersections are 8 m at 0.76% U_3O_8, 28 m at 0.38% U_3O_8, and 13 m at 0.36% U_3O_8.

Ranger 4 is 5 km west-southwest 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 1 600 000 lbs of U_3O_8 (726 t); it has not been fully delineated.

The Jabiluka joint venturers also stated that further drilling at the **7J** prospect, 3 km northeast of Hades Flat, 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** deposit is 21.5 km south-southeast of the Nabarlek deposit. 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 Formation sandstone.

The **Austatom** prospect is 28 km west of the Ranger 1 deposits. The uranium mineralisation, in weathered Cahill Formation schist, 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. The best auger hole intersections, as stated by the Australian Atomic Energy Commission (AAEC) in a press release in December 1976, were 4.8 kg/t U_3O_8 over 1.5 m and 2.1 kg/t U_3O_8 over 13 m.

Uranium prospects have been discovered within the Arnhem Land Aboriginal Reserve, 36 km south-southwest of Nabarlek at **Beatrice,** 15 km southwest of Nabarlek at **Gurrigarri** and **Garrunghar,** and 8.5 km southwest of Nabarlek at **Mordijmuk;** and also at **Arrarra,** 35 km north of Jabiluka (Hegge & others, 1980).

Resources and production

Total proved and probable resources in the Alligator Rivers uranium field, as published by the various companies (Table 7), amount to 335 426 t U_3O_8, with another 12 213 t U_3O_8 of possible resources in the No. 3 Orebody at Ranger 1. Total production from the Ranger 1, No. 1 Orebody up to 1 July 1986 amounted to 14 886 t U_3O_8, and Nabarlek had produced 8325 t U_3O_8 up to 1 July 1986.

Table 7. Published uranium resources (U_3O_8), major deposits, Alligator Rivers uranium field, as at 1 July 1986

	Grade (%)	*Tonnes*	*Reference and year published*
RANGER 1			
No. 1 Orebody	0.328	31 652 proved	Energy Resources of Australia Ltd (1986)
	0.147	329 probable	
Stockpiled	0.308	6 834	
No. 3 Orebody	0.207	72 838 probable	
	0.163	12 213 possible	
JABILUKA 1	0.25	3 400	Pancontinental Mining Ltd (1979)
JABILUKA 2	0.39	204 000	
KOONGARRA			
No. 1 Orebody	0.269	13 300	Noranda Australia Ltd (1979)
No. 2 Orebody	—	2 300	
NABARLEK	1.84	773(a) (in ore stockpile)	

(a) Final EIS (January, 1979) stated the in-situ resource as 9098 t U_3O_8, from which production to 1 July 1986 (8325 t) has been deducted.

Rum Jungle uranium field

The Rum Jungle uranium field (Fig. 14), 90 km south of Darwin, was the first to be discovered in the Pine Creek uranium province. A total of 3530 t U_3O_8 was recovered at the Rum Jungle treatment plant from 1954–1971, from four deposits in the Rum Jungle field and from 10 000 t of custom-treated ore from elsewhere.

The initial discovery was made by Mr J.M. White in 1949, who reported that some minerals in outcrops northeast of Rum Jungle railway siding resembled uranium minerals illustrated in the booklet, 'Radioactive Mineral Deposits', published by BMR in 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.

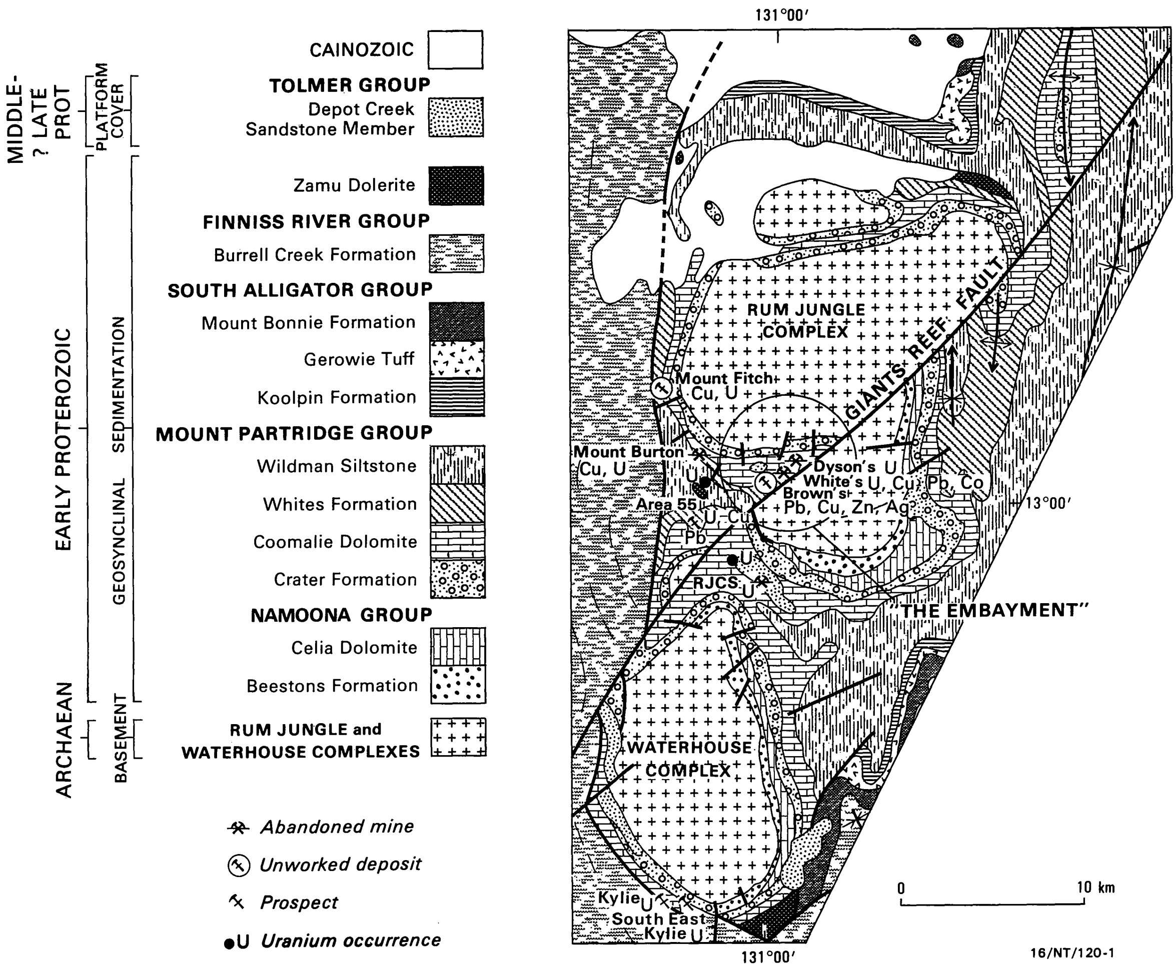

Fig. 14. Geology of the Rum Jungle uranium field (after Ewers & others, 1984).

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

In 1953 Territory Enterprises Pty Ltd (TEP), a subsidiary of Consolidated Zinc Proprietary 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 km², 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/annum from ores grading 0.23 to 0.35% U_3O_8 (Warner, 1976; Barlow, 1962).

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 & 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 Geosyncline (Figs. 5 and 6) where Early Proterozoic metasediments are unconformably draped around two Archaean granitic basement complexes (Fig. 14) — the Rum Jungle Complex to the north and the Waterhouse Complex to the south (Fraser, 1980; Crick, in press.). 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 Early Proterozoic sequence is locally unconformably overlain by hematite quartzite breccia (Buckshee Breccia — a regolith?) and by Middle–?Late Proterozoic sandstone and conglomerate.

The Early Proterozoic 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 southeastern 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 northeast, followed to the southwest by White's (uranium, copper, lead, cobalt, nickel), Intermediate (copper, uranium; immediately southwest of White's), and Brown's (lead, zinc, copper, cobalt, nickel; 1 km southwest 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 northwest of White's. Rum Jungle Creek South (uranium; 'RJCS' in Figure 14) is 5 km southwest 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 Cu, Co, and Pb 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.

Deposits

Four deposits were mined in the Rum Jungle uranium field, two of which also produced copper. The amounts of uranium ore mined from the various open cuts, as given in Table 8, are derived from Berkman (1968). Copper was mined from the Intermediate open cut.

Table 8. Uranium and copper ore treated from the Rum Jungle uranium field (a)

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

(a) Copper ore was also mined from the Intermediate open cut.

The figure of 403 000 t mined from White's (as shown in Table 8) includes 87 000 t of low-grade uranium-copper ore which Berkman (1968) states was treated at the plant, whereas Warner (1976) excluded this material. Regardless of whether this material was treated at the plant, 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 (1953–1954), TEP mined the deposit by both underground and open-cut methods, with further open-cut mining in 1954–1957, 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.

White's deposit is approximately 1 km southwest of Dyson's. Like Dyson's, White's was first (1953) mined underground but during 1954–1958 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 in excess of 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, & 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 & 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 Early Proterozoic Whites Formation near its unconformable contact with the Middle Proterozoic sandstone and breccia-conglomerate of the Depot Creek Sandstone Member. The primary ore assemblage is dominated by pitchblende, which together with chlorite and/or sericite and hematite occupies kinked and brecciated zones associated with post-Middle Proterozoic 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 is proposed for the origin of the uranium mineralisation, and two generations of uranium mineralisation have been identified (Paterson & others, 1984).

Southeast 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 southwestern 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. 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 1961–1963 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 weathering 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

1966–1970 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 & 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 of 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). UAL 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.

UAL found the **Kylie** prospect in 1978 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 Middle Proterozoic Depot Creek Sandstone Member. 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 **Southeast Kylie** prospect is 2 km southeast 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 southeast of Mount Burton; and **Rum Jungle Creek** and **Area 55,** 1 km and 4.5 km northwest of the Rum Jungle Creek South open cut. The **Waterhouse** prospects are south of the Rum Jungle Complex and east of the Waterhouse Complex. 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-northeast and northeast respectively of White's (Crick, in press).

South Alligator Valley uranium field

The smallest uranium field in the Pine Creek uranium province is in the South Alligator River valley, 220 km southeast of Darwin (Figs. 5 and 15). 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 northwest-trending structural belt 24 km long and 3 km wide. Between 1956 and 1964 some 874 t of U_3O_8 (Table 9) 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

Table 9. Production from the South Alligator Valley uranium mines (after Foy, 1975)

	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 Sterrits)	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

was treated at Moline, about 48 km west of the field in a plant converted to solvent extraction of uranium. Some ore was treated at a much smaller plant at the Rockhole mine. 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 has been reported. Recently the area has become more significant for its potential for gold and platinum-group elements.

Regional geological setting

The field lies within a northwesterly-trending zone of folded and faulted Early Proterozoic metasediments exposed in the South Alligator valley (Fig. 15). In ascending stratigraphic order (Crick, Muir, Needham, & Roarty, 1980), the Early Proterozoic sequence comprises carbonaceous shale, siltstone, quartzite, and dolomitic metasediment of the Masson Formation, followed by intermediate volcanics (Stag Creek Volcanics). Unconformably overlying the volcanics are coarse clastics of the Mundogie Sandstone, which in turn are unconformably overlain by ferruginous carbonaceous siltstone, chert bands, and dolomitic metasediments of the Koolpin Formation. The Early Proterozoic succession continues with felsic to andesitic volcanics of the Gerowie Tuff and Shovel Billabong Andesite. The Koolpin Formation has been extensively intruded by sills of the Zamu Dolerite.

The Early Proterozoic succession described so far represents geosynclinal strata folded and metamorphosed between 1870 and 1800 Ma. Felsic volcanics and associated volcanoclastics and epiclastics (El Sherana and Edith River Groups) were deposited during the post-orogenic phase (also Early Proterozoic) and rest unconformably on the metasediments (Stuart-Smith, Needham, Roarty, & Crick, 1984). At 1690 Ma, the Early Proterozoic rocks were intruded by the Oenpelli Dolerite. After a period of erosion and folding/tilting, the Middle Proterozoic Kombolgie Formation was deposited, at about 1650 Ma.

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

Most of the uranium mineralisation was present in the ferruginous cherty shale of the Koolpin Formation. Sandstone and rhyolite of the El Sherana Group also contained uranium deposits where these rocks are faulted against primary uranium mineralisation in the geosynclinal sediments. Syngenetic deposition of uranium in carbonaceous shale of the Koolpin Formation, followed by supergene enrichment, were modes of origin proposed by Condon & Walpole (1955) and Prichard (1965). Threadgold (1960) and Shepherd (1962) proposed

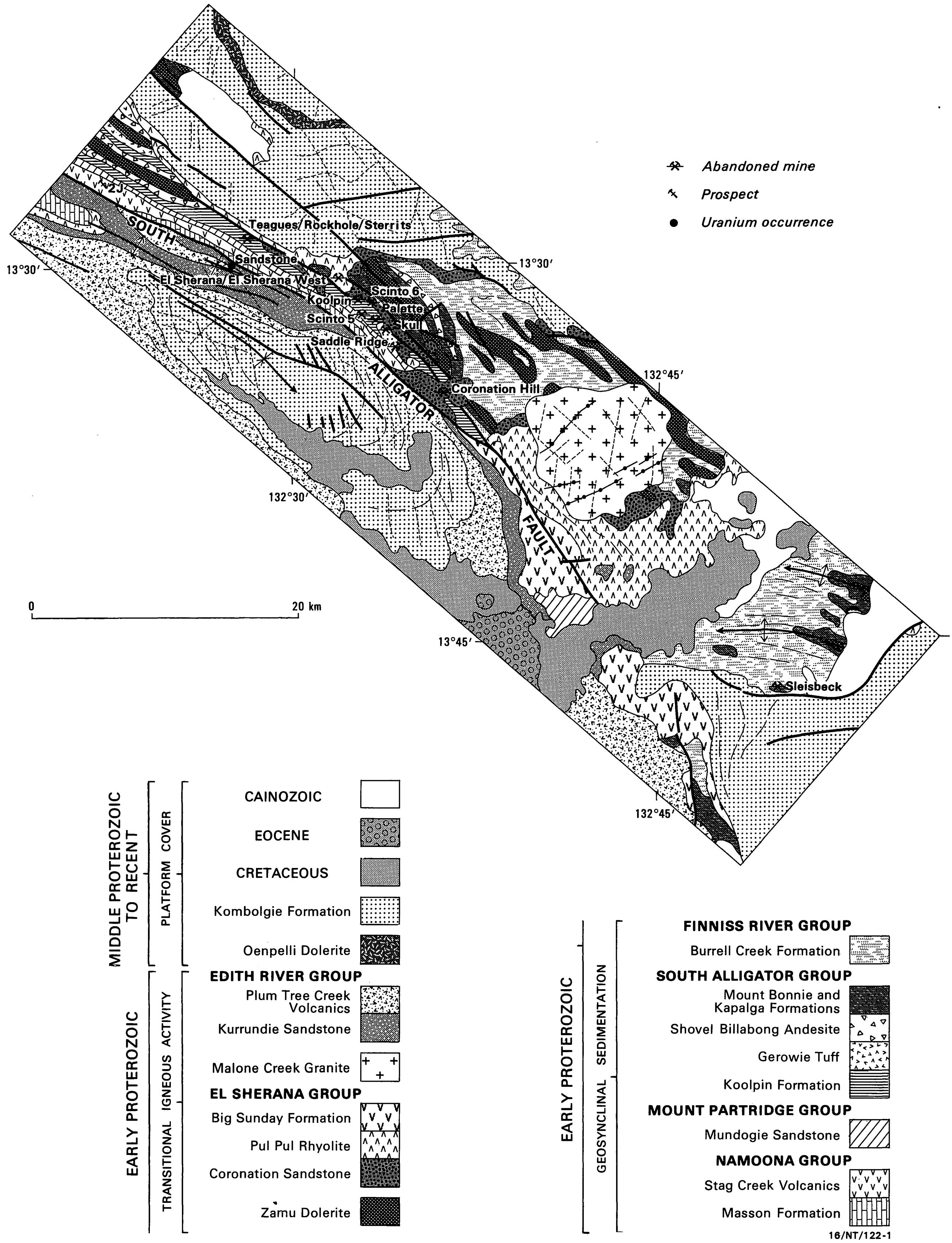

Fig. 15. Geology of the South Alligator Valley uranium field (from Ewers & others, 1984).

deposition of uranium from ascending solutions. Ayres & Eadington (1975) advocated precipitation of uranium from circulating groundwater that derived uranium from volcanic rocks of the El Sherana Group.

Deposits

Virtually all of the uranium production was obtained from 13 small deposits in the upper reaches of the South Alligator River valley. Several were on precipitous ridges along the northeastern side of the valley in a northwest-trending zone 20 km long, from the Rockhole Mine in the northwest to Coronation Hill in the southeast. The Sleisbeck deposit, which also recorded production, is a further 30 km southeast of Coronation Hill.

At four of the mined deposits — **El Sherana West, Rockhole No. 2, Scinto 5,** and **Koolpin Creek** — the pitchblende ore occurred in cherty ferruginous shale of the Koolpin Formation (Prichard, 1965; Crick & others, 1980). At **El Sherana** and **Sterrits,** most of the ore was in the Koolpin Formation but some was in the adjacent Coronation Sandstone of the El Sherana Group. At **O'Dwyers** and **Palette,** pitchblende was present in both the Koolpin Formation and the Coronation Sandstone. At **Rockhole No. 1** and **Skull,** pitchblende was largely confined to the Coronation Sandstone. At **Scinto 6** the pitchblende was in altered rhyolite of the Coronation Sandstone (Needham & Stuart-Smith, 1985). The **Coronation Hill** deposit was in a polymictic debris-flow conglomerate of the Coronation Sandstone (Needham & Stuart-Smith, 1986). The conglomerate consists of rounded to angular clasts of quartz, quartzite, sandstone, carbonaceous shale, rhyolite, and volcaniclastics in a greywacke matrix. Needham & Stuart-Smith (1986) have proposed that the Coronation Hill deposit is an epigenetic sandstone-type uranium deposit, rather than an unconformity-type. All of the uranium mineralisation at **Saddle Ridge** consisted of secondary minerals. At **Sleisbeck,** pitchblende occurred in chlorite schist of the Kapalga Formation. Secondary uranium mineralisation at the **2J** prospect, 30 km northwest of Coronation Hill, is in the Stag Creek Volcanics (Foy & Miezitis, 1977).

The main uranium ore mined was pitchblende, in disseminated veinlets and large discrete masses. Secondary uranium minerals included phosphuranylite, metatorbernite, autunite, uranophane, soddyite, and gummite.

Gold was present at most of the deposits and was recovered from Palette, Coronation Hill, El Sherana, and El Sherana West. Recent exploration at Coronation Hill, has outlined significant gold-platinum mineralisation (Noranda Pacific Ltd, 1985). It was reported that the whole zone of the El Sherana Group acid volcanics along the South Alligator River fault system can now be regarded as a major target for gold and platinum-group-element exploration.

Sulphide and other primary minerals are present in very minor amounts and include galena, pyrite, chalcopyrite, niccolite, gersdorffite, clausthalite, and coloradoite.

Turee Creek area

The Turee Creek area is in the Pilbara region, 1200 km north-northeast of Perth (Fig. 16). In 1972 Noranda Australia Ltd conducted an airborne radiometric survey along the Early/Middle Proterozoic 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 Middle Proterozoic sedimentary strata of the Bresnahan Basin, about 16 km north-northwest 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 Early/Middle Proterozoic 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 it occurs at a contact between Middle Proterozoic sandstone and Early Proterozoic shale, greywacke, and dolomite of the Mount McGrath Formation (Wyloo Group). The most significant mineralisation was found in 1980–81, and investigations are continuing (Lustig, Ewers, Williams, & Ferguson, 1984).

Regional geological setting

The Turee Creek area (Lustig & others, 1984) is at the boundary between the Early Proterozoic Hamersley Basin and the Middle Proterozoic Bresnahan Basin (Fig. 16). Early Proterozoic metasediments of the Wyloo Group form a trough, the Ashburton Fold Belt, along the southwestern margin of the Hamersley Basin, and are unconformably overlain by the unmetamorphosed arenitic clastics of the Bresnahan Group.

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 the Cherrybooka Conglomerate and arenite and arkose of the Kunderong Sandstone.

The 'Noranda' prospect lies just outside the northern margin of the Ashburton Fold Belt, where the Kunderong Sandstone is underlain by the Woongarra Volcanics of the Hamersley Group.

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 at the contact between the Early Proterozoic Wyloo Group and the Middle Proterozoic Kunderong Sandstone. The nature of this contact is controversial: it may be a fault, or an unconformity along which there has been minor movement.

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 and has not yet been fully delineated. Mineralisation has a maximum width of 8.5 m and a grade of 0.047% U_3O_8. The host rock is clay, carbonaceous in part, and brecciated Kunderong Sandstone. 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.

The **'Noranda'** prospect found by Noranda Australia Ltd is 16 km north-northwest of Turee Creek station in arkose of the Bresnahan Group. 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 Early/Middle Proterozoic 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, October 1984; Noranda Pacific Ltd, 1985).

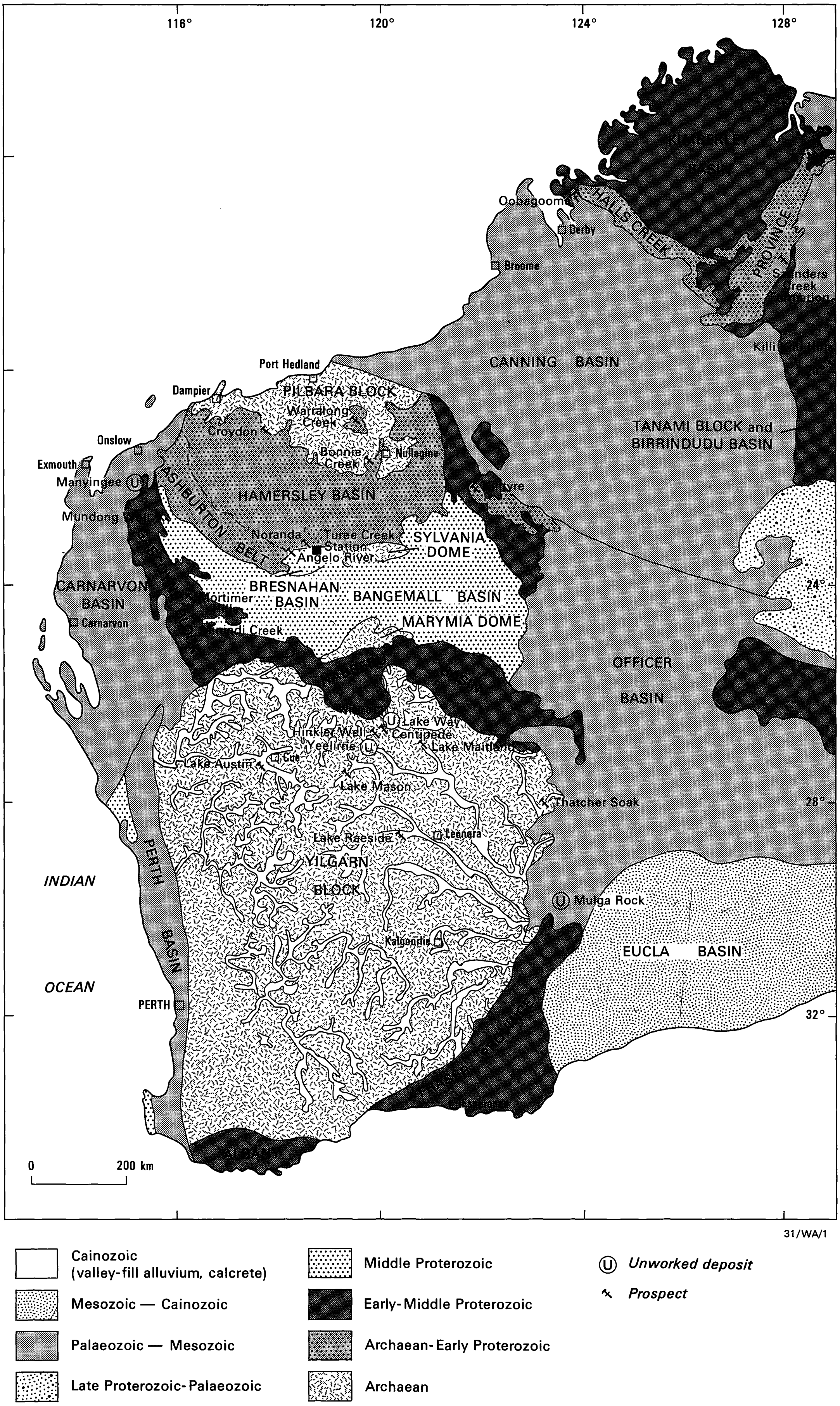

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Fig. 16. Geological provinces of Western Australia, and locations of principal uranium deposits and prospects (Tertiary drainage channels are shown only on the Yilgarn Block).

Some minor occurrences of uranium have been located in the Early Proterozoic 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.

Killi Killi Hills area

There are two uranium prospects in the Killi Killi Hills area, 230 km southeast of Halls Creek, in Western Australia near the Northern Territory border. Early Proterozoic schistose to phyllitic greywacke, arenite, and siltstone of the Killi Killi Beds and the Early Proterozoic Pargee Sandstone, are overlain by Middle Proterozoic sedimentary rocks of the Birrindudu Basin in a major regional unconformity (Blake, Hodgson & Muhling, 1979). The uranium mineralisation is in coarse lithic arenite, conglomerate, and micaceous siltstone of the Gardiner Sandstone at the base of the Birrindudu Group. Mineralisation appears to be associated with fault zones. The main uranium-bearing mineral is xenotime, a rare-earth-uranium phosphate. The regional geology of this area is similar to the Pine Creek Geosyncline. Recent exploration has been targeted at the Early Proterozoic metasediments along the unconformity (Western Australia Department of Mines, 1980; Carter, 1981; Blake & Hodgson, 1975).

Halls Creek area

In the Halls Creek area there has been extensive exploration for unconformity-related uranium mineralisation. In some respects the regional geology is similar to the Pine Creek Geosyncline.

The Halls Creek Province comprises Archaean–Early Proterozoic geosynclinal sedimentary rocks of the Halls Creek Group. These sedimentary rocks were intruded by a variety of Early Proterozoic igneous rocks including granite, quartz-feldspar porphyry, and rhyolite referred to as the Lamboo Complex. The Halls Creek Group has been metamorphosed in many areas. These units are unconformably overlain by gently folded and unmetamorphosed Middle Proterozoic sedimentary and volcanic rocks which form the Kimberley Basin (Carter 1976, 1981).

To date only minor mineralisation in shear zones in granite of the Lamboo Complex and ironstone of the Halls Creek Group has been found (Carter 1976, 1981).

Quartz-pebble conglomerates of the Saunders Creek Formation (Halls Creek Group) and King Leopold Sandstone (base of the Kimberley Basin) have been extensively explored for uranium (see section on 'Quartz-pebble conglomerate uranium deposits').

Tennant Creek area

The Early Proterozoic Warramunga Group comprises shale, siltstone, greywacke, and interbedded volcanics in the Tennant Creek Block, NT. These are intruded by Early to Middle Proterozoic granite and adamellite (Dodson & Gardener, 1978; Black, 1981). At the **Edna Beryl** and **Northern Star** prospects, 40 km north of Tennant Creek, uranium is associated with gold in hematitic shale of the Warramunga Group (Ingram, 1974). The Middle Proterozoic Tompkinson Creek Beds, which unconformably overlie the Warramunga Group, crop out 5 km north of the Edna Beryl prospect. In the Mosquito Creek area, 85 km southeast of Tennant Creek, uranium occurs in a shear zone in granite.

Southwestern Eyre Peninsula

The Precambrian terrane lying about 50 km south of Kimba (SA) has been explored for unconformity-related uranium in the late 1970s and early 1980s (South Australia Department of Mines & Energy, 1985). This area contains Archaean granite and gneiss of the Sleaford Complex overlain by metamorphosed sedimentary strata of the Early Proterozoic Hutchinson Group and by younger (Early Proterozoic) gneiss and migmatite of the Lincoln Complex. All of these rocks are overlain by the Carpentarian Corunna Conglomerate. Only minor occurrences of pitchblende have been found near the contact between the Lincoln Complex and the Hutchinson Group (South Australia Department of Mines & Energy, 1982b).

PROTEROZOIC STRATIFORM AND STRATABOUND DEPOSITS

Stuart Shelf region

The potential of the Stuart Shelf region (Fig. 17) for uranium mineralisation became apparent in 1975 when Western Mining Corporation Ltd (WMC) discovered the very large Olympic Dam copper-uranium-gold deposit. The deposit is 650 km north-northwest of Adelaide, on Roxby Downs Station.

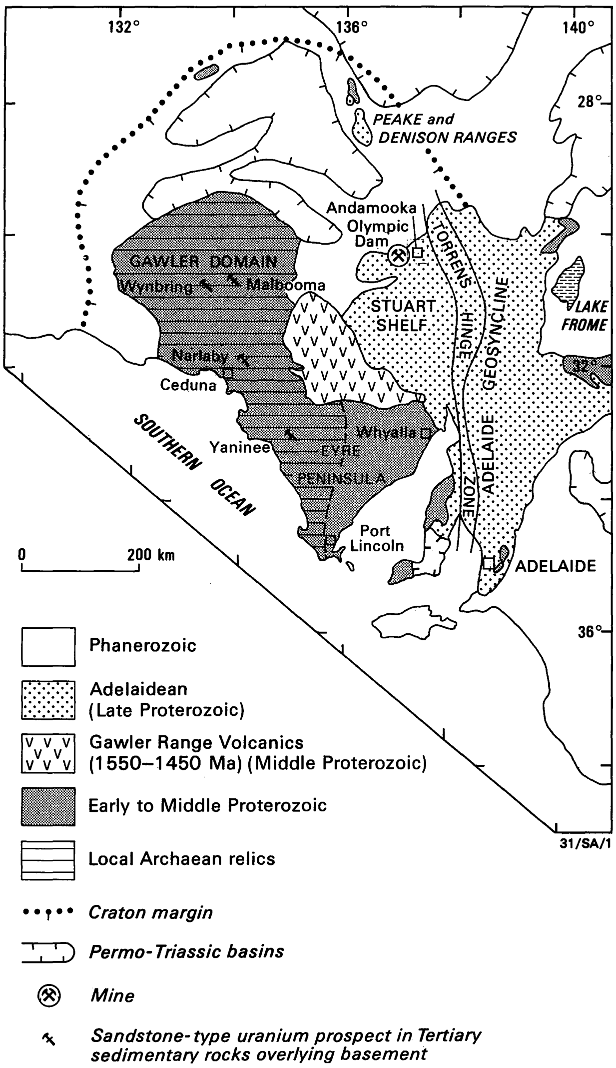


Fig. 17. Major geological provinces and units in part of South Australia, and locations of uranium deposits and prospects.

The original exploration target, formulated by WMC (for copper), was chosen from two different lines of study. One was a conceptual geological model which related the formation of stratabound copper deposits to solutions that had acquired copper during oxidative alteration of basalts (Haynes, 1979; Roberts & Hudson, 1983); the other was based on tectonic studies and lineament analysis (O'Driscoll, 1982 and 1983). At Olympic Dam the geophysical response of the target consisted of coincident regional gravity and magnetic anomalies previously delineated in regional surveys by BMR and the South Australian Department of Mines & Energy. These anomalies were thought to represent concealed piles of altered basalt within flat-lying sedimentary rocks (Haynes, 1979).

The first drillhole (RD1) intersected 38 m of 1.05% Cu at a depth of 353 m. More holes were drilled, and the potential of the area was highlighted in November 1976 by results from RD10 which intersected 170 m of 2.1% copper and over 0.05% U_3O_8.

In order to delineate the prospect an extensive drilling program was commenced in 1979 by a joint venture between Roxby Mining Corporation, a wholly owned subsidiary of WMC and BP Australia Ltd, and BP Petroleum Development Ltd. An exploration shaft was sunk to a depth of 500 m between January 1981 and mid-1982 and underground exploratory driving and drilling began. The construction of a pilot treatment plant was completed in 1984 and a feasibility study of the project was completed during 1985. On 8 December 1985 the joint-venture partners announced their commitment to construct a mine, with a scheduled annual production rate of 2000 t U_3O_8, 55 000 t of copper, and 90 000 oz of gold.

The discovery of Olympic Dam attracted many other exploration companies to the area, and in 1979, WMC reported the discovery of the Acropolis copper-uranium prospect, 25 km southwest of Olympic Dam. However, no further significant uranium discoveries in the Stuart Shelf region have been announced.

Regional geological setting

The Olympic Dam deposit is in a Middle Proterozoic basement sequence beneath the Late Proterozoic (Adelaidean) to Cambrian strata of the Stuart Shelf (Fig. 17). Roberts & Hudson (1983) have subdivided the basement sequence into the Olympic Dam Formation and the younger Greenfield Formation. These formations are regarded as equivalent to the youngest component of the Gawler domain; they were not metamorphosed during the Kimban orogeny, and are therefore regarded as younger than 1580 Ma.

The unconformably overlying Late Proterozoic to Cambrian sedimentary strata of the Stuart Shelf are flat-lying.

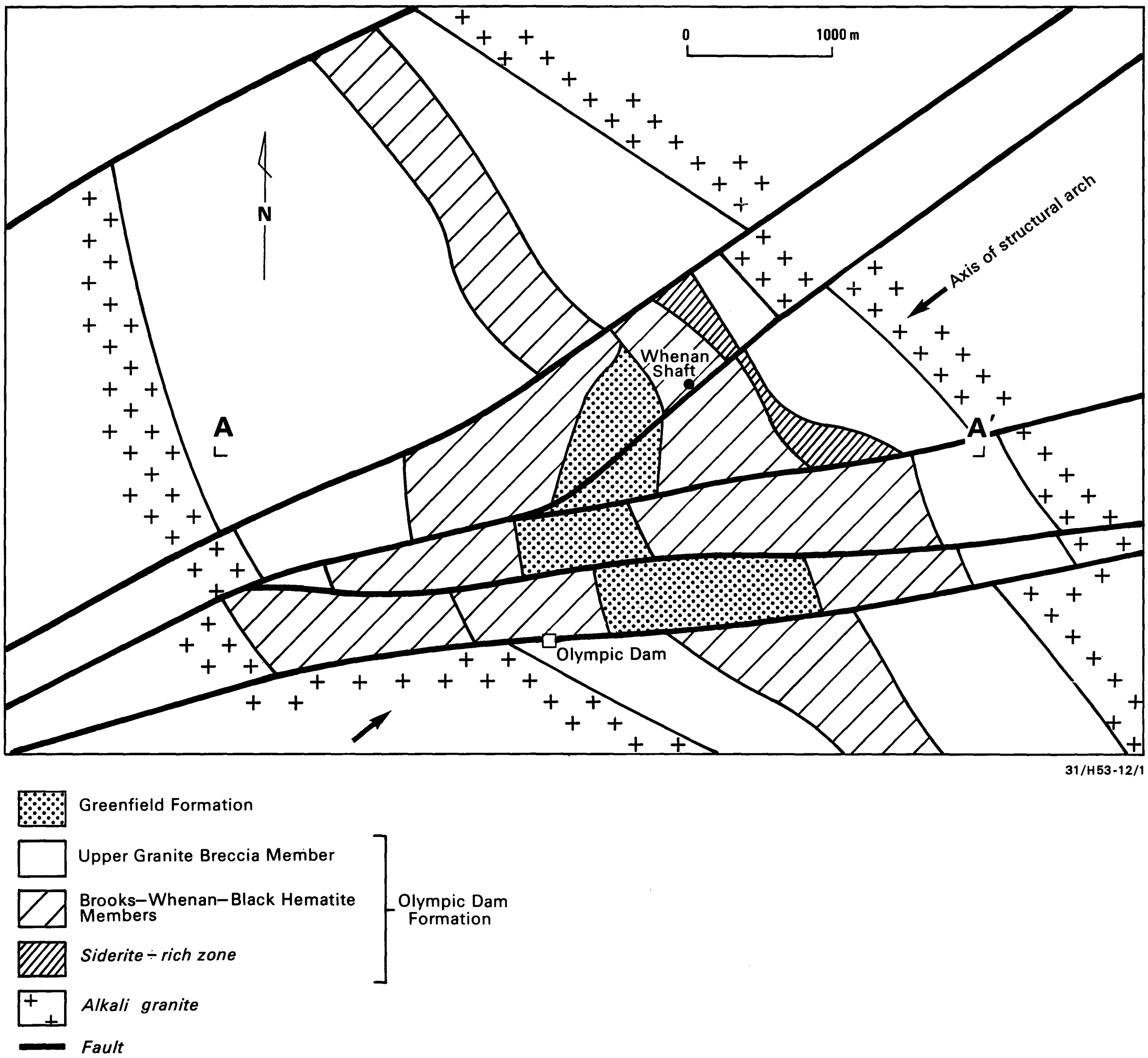


Fig. 18. Generalised geology at the Olympic Dam deposit, SA, at the –450 m level (after Roberts & Hudson, 1983).

To the east, the Stuart Shelf is bounded by the major Torrens Hinge Zone (Thompson, 1969; Preiss, Rutland & Murrel, 1980) which separates it from the Adelaide Geosyncline. To the southwest its strata lap onto the Gawler Craton. To the north and northwest they are overlain by the late Palaeozoic and Mesozoic strata of the Arckaringa and Great Artesian basins.

The Olympic Dam deposit occupies a structural basement high and the flat-lying cover strata are some 350 m thick; generally elsewhere in the Stuart Shelf these strata are more than 1000 m thick.

O'Driscoll (1982 and 1983) showed that the Olympic Dam deposit is associated with a narrow west-northwesterly structural corridor where it crosses a major north-northwesterly gravity corridor.

Olympic Dam deposit

The Olympic Dam deposit lies within a basement sequence of very coarse, unmetamorphosed, sedimentary breccias comprising the Olympic Dam Formation and the younger Greenfield Formation (Figs. 18 and 19). Both formations are of Middle Proterozoic age, and occupy a northwest trending trough or graben. To the northeast, southwest, and northwest the breccias are faulted against the Myall Granite, which is also assumed to stratigraphically underlie the breccias. The breccia sequence is thicker than 1000 m, and ranges from matrix-poor granite breccia to matrix-rich polymict breccia.

The Olympic Dam Formation has five members of which the Black Hematite, Whenan, and Brooks members are matrix-rich and contain the bulk of the ore. Clast types include Myall Granite, felsic, intermediate, and mafic volcanics, hematite, terrigenous sedimentary rock, carbonate, fluorite, barite, and sulphides. The matrix of the breccias is mainly hematite. There is also some mineralisation in the Upper Granite Breccia member but there is no significant mineralisation in the Lower Granite Breccia.

The Greenfield Formation has three members and occupies downfaulted blocks. The dominant rock types are hematite-rich breccia, volcanic breccia, and iron formation. Mineralisation occurs in the lower part of the Greenfield Formation, mainly in the Lower Silicified Member.

Two main types of mineralisation have been recognised:

— generally flat-lying to gently dipping zones of *stratabound* bornite-chalcopyrite-pyrite with associated uranium, rare-earth minerals, and gold varying from 30 to 350 m in thickness;

— higher-level *transgressive* zones of *epigenetic* chalcocite-bornite with associated uranium, rare-earth minerals and gold with intersections up to 300 m in thickness and confined to a linear northwest-trending zone.

The stratabound bornite, chalcopyrite, and pyrite mineralisation occurs as free grains and aggregates in the three hematite-matrix-rich breccia members of the Olympic Dam Formation. The ore contains 5 to 20% sulphides. Uraninite, coffinite, and brannerite, and the rare-earth-element minerals bastnaesite and florencite, are intimately associated with the copper and iron sulphides. Minor amounts of covellite, carrollite, and cobaltite are present. A vertical zoning is evident within the deposit, from a sulphur-rich, copper-poor assemblage at the base to a copper-rich, sulphur-poor assemblage at the top. Laterally there is a distinct siderite-rich zone along the northeastern edge of the deposit.

The transgressive chalcocite-bornite mineralisation occurs as massive sulphide clasts, veins, rims on clasts, and cavity fillings. It usually occurs in the Upper Granite Breccia Member, but is not confined to it. Uranium and rare-earth minerals are the same as in the stratabound mineralisation.

In June 1982, WMC announced that 'the estimated amount of mineralisation so far drilled on a 200 m grid is about 2000 million tonnes at an average grade of 1.6% copper, 0.06% U_3O_8, and 0.6 g/t gold'. Drilling has shown mineralisation at Olympic Dam to extend over an area of 7 km by 4 km.

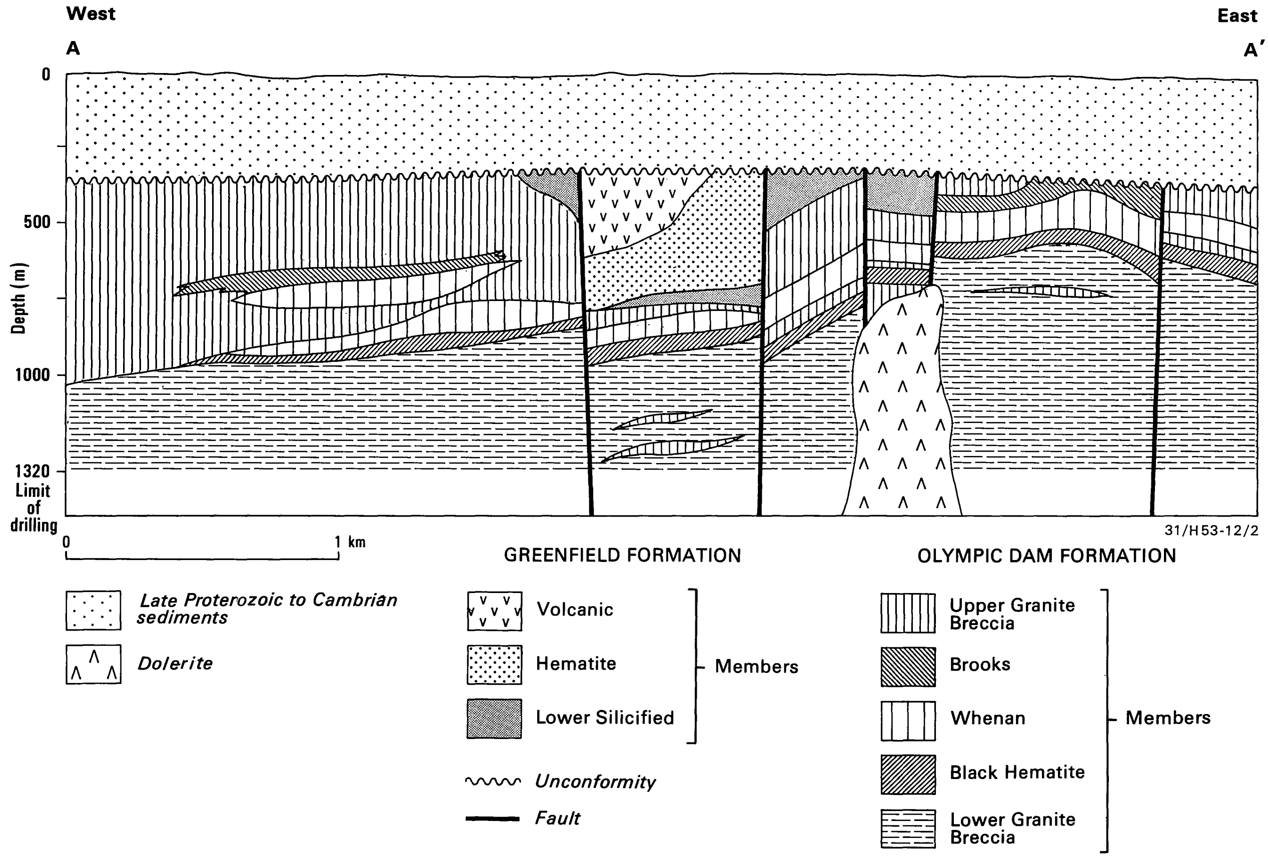


Fig. 19. Olympic Dam deposit, SA: cross-section along mine grid 200 000 N (after Roxby Management Services Pty Ltd, 1982).

In November 1983, WMC stated that exploration and development work in the mineralised area had established 'a probable 450 million tonnes of higher-grade ore averaging 2.5% copper, 0.08% U_3O_8, 0.6 g/t gold and 6 g/t silver'.

Other deposits

At the **Acropolis** prospect, 25 km southwest of Olympic Dam, WMC reported an intersection of 66 m (924–990 m) of 0.7% copper and 0.003% U_3O_8, in mineralisation similar to that at Olympic Dam.

SANDSTONE DEPOSITS

Frome Embayment uranium field

Oilmin NL and Transoil NL explored the Proterozoic rocks of the North Flinders Ranges in South Australia for uranium during the mid 1960s. In 1968, together with Petromin NL, they began an assessment of the uranium potential of the Tertiary sands to the east, which have been derived from the uranium-rich metamorphics in the Mount Painter area (Fig. 20). Rotary-percussion drilling began the following year and

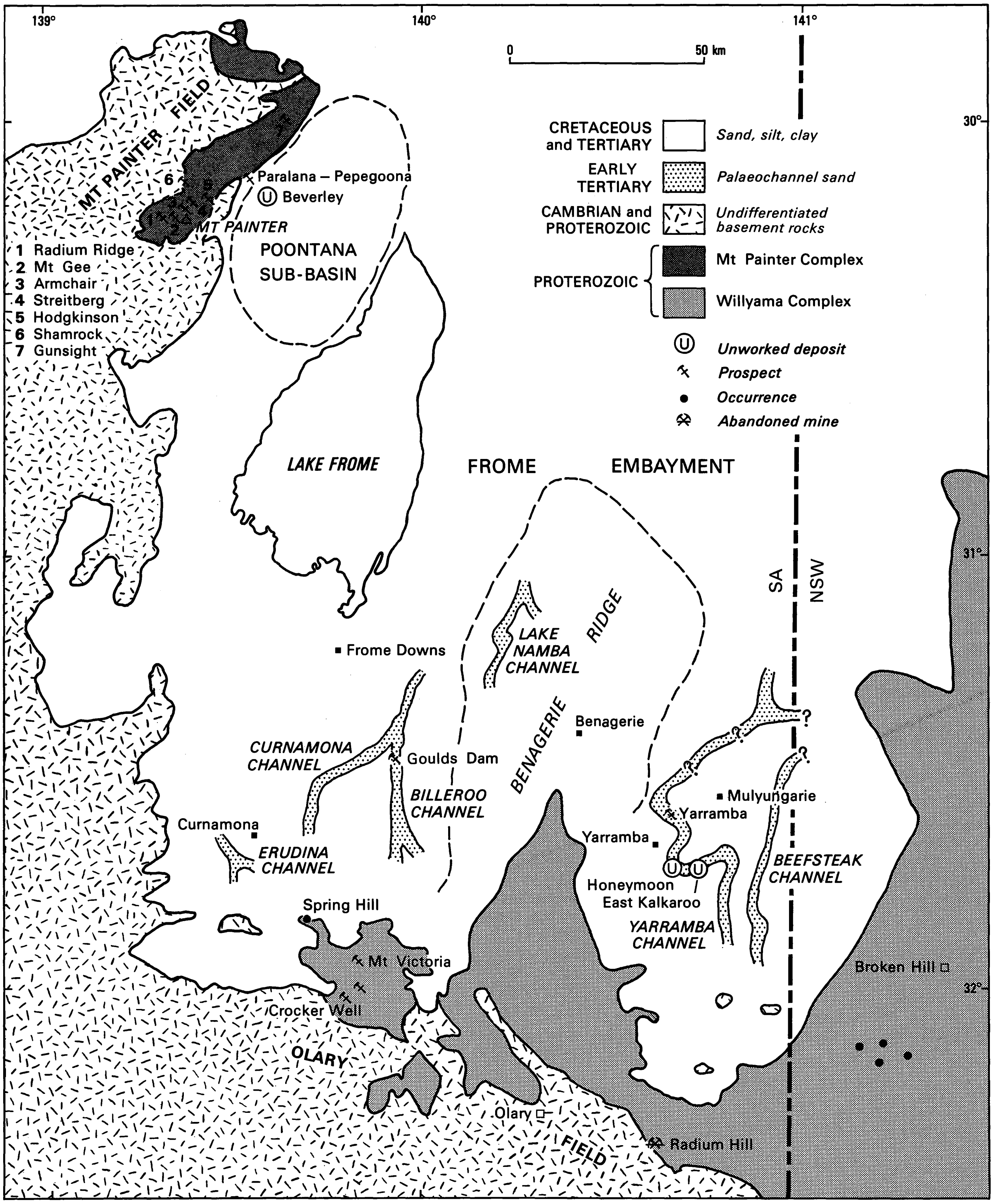


Fig. 20. Regional geology of the Frome Embayment and environs showing Tertiary palaeochannels and uranium deposits, prospects, and minor occurrences (locations of palaeochannels after Brunt, 1978).

the first rocks to be tested were sedimentary breccias flanking the Flinders Ranges. Early drilling was difficult because of large granite blocks in scree in the upper part of the section. No significant radioactivity was found in the sediments close to the ranges. Holes drilled further east in the Poontana Sub-basin intersected low-grade mineralisation in the vicinity of the Beverley deposit. The first hole to intersect economic-grade mineralisation at the Beverley deposit was drilled in 1970. Up till then 10 000 m of drilling had been completed (Haynes, 1975). In June 1972, Western Nuclear Australia Ltd signed a joint-venture agreement with the Oilmin-Transoil-Petromin Group to fund exploration and development drilling. Western Nuclear Australia Ltd later earned a 50% equity in the project.

Following the Beverley discovery, there was a rapid increase in uranium exploration throughout the Frome Embayment by many exploration companies.

Sedimentary Uranium NL explored early Tertiary palaeochannels in the southern part of the embayment, and discovered the Yarramba deposit in 1970 and the East Kalkaroo deposit in 1971 (Sedimentary Uranium NL, 1971; Brunt, 1978).

During 1971 and 1972, Carpentaria Exploration Co. (CEC) carried out reconnaissance-drilling over a nearby area. Minor uranium mineralisation was recorded in a number of holes, as reported later by Mines Administration Pty Ltd (1981) — exploration including drilling was continued by Mines Administration and Teton Exploration Drilling Co. Pty Ltd (Teton) under a farm-in agreement. Reconnaissance resistivity traversing was used to locate buried palaeochannels. The stratigraphy and possible mineralisation in these channels were then rotary-drilled and gamma-ray logged (Brunt, 1978). During 1972, mineralisation was intersected in what is now known as the Honeymoon deposit.

In 1974, the Minad-Teton-CEC joint venture discovered the Goulds Dam deposit by exploration drilling in the Billeroo Channel (Brunt, 1978).

Regional geological setting

The regional geology of the Frome Embayment has been described by Coates, Horwitz, Crawford, Campana, & Thatcher (1969); Coates & Blisset (1971); Wopfner, Callen, & Harris (1974); Callen (1975, 1981); Brunt (1978); and the South Australian Uranium Corporation (1983). The Frome Embayment is a lobe on the southern margin of the intermittently marine Jurassic–Cretaceous Eromanga Basin, and also contains Cainozoic strata (Table 10). The Flinders, Olary, and Barrier Ranges flanking the basin consist mainly of Precambrian and Cambrian metamorphics and sedimentary rocks which contain many small uranium deposits and widespread disseminated uranium mineralisation. Intermittent terrestrial sedimentation in the Cainozoic produced a thin sequence of flat-lying strata.

During the Early Tertiary, well-sorted sand (Eyre Formation) was deposited as a thin, laterally continuous horizon covering the full width of the basin in the north (Wopfner & others, 1974). In the south, the Eyre Formation equivalents — angular, micaceous, poorly sorted, fluvial sand and interbedded clay and silt — were deposited in major stream channels of restricted areal extent (Brunt, 1978). The channels were incised into marine clay of the Late Cretaceous Marree Subgroup and Precambrian basement.

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

The Honeymoon, East Kalkaroo, Yarramba, and Gould's Dam deposits are in palaeochannel sand of the Eyre Formation (Palaeocene–Eocene) whereas the Beverley deposit is in sand of the overlying Namba Formation (Miocene).

The palaeochannels in the southern part of the Frome Embayment flank a buried structural high, the Benagerie Ridge.

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

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

Table 10. Regional stratigraphy of the Frome Embayment

	Age	*Lithology*	*Average thickness (m)*	*Uranium deposits*
Coonarbine, Eurinilla, & Millyera Formations; various unnamed units	Pleistocene to Recent	Soil, dune sand, sand, clay, gravel, calcrete, gypcrete	Variable, thin	
Willawortina Formation	Late Miocene to Early Pleistocene	Bouldery to pebbly silty clay or sandy conglomerate and dolomite	0–150	
Namba Formation	Miocene	Silt and clay, with minor sand, limestone, and dolomite	200	Beverley
		DISCONFORMITY		
Eyre Formation	Early Palaeocene to Late Eocene	Sand and sandstone, some pebble beds	10–75	Honeymoon, East Kalkaroo, Yarramba, Gould's Dam
		UNCONFORMITY		
Marree Subgroup	Cretaceous	Shale and siltstone	150–275	
Cadna-Owie Formation and Algebuckina Sandstone	Jurassic to Cretaceous	Shale, sand, silt, and boulder lenses	55	

Source: South Australian Uranium Corp. (1983); Callen (1981).

Beverley deposit

The Beverley deposit comprises several large flat-lying lenses of uranium mineralisation in a porous sand unit of the Namba Formation. The sand and interbedded clay also contain widespread disseminated mineralisation. The palaeochannel at Beverley differs from those in the southern part of the embayment in that it does not have a well-defined trough-like shape. The channel was probably formed by a meandering stream (South Australian Uranium Corp., 1983); it contains marked changes in facies across and along its length, but there is a central sinuous zone of clean sand passing laterally into silty sand and then into interlayered clays.

The uranium mineralisation is in quartz-feldspar sand containing some kaolinite and montmorillonite. The primary uranium minerals are coffinite and uraninite. Organic carbon ranges up to 0.5% in the mineralised zones (South Australian Uranium Corp., 1983).

The in-situ resources at Beverley are estimated as 6 Mt of ore averaging 0.27% U_3O_8; this comprises 16 200 t of contained U_3O_8, of which it is estimated that 11 500 t U_3O_8 could be recovered by in-situ solution mining, assuming a 70% recovery (South Australian Uranium Corp., 1983).

Honeymoon deposit

The Honeymoon deposit is in the Yarramba Channel, at the margins of a zone of oxidised sand and clay of the Eyre Formation. Uranium was precipitated at a redox boundary along the outer edge of a broad bend in the channel; permeability was less there because of the greater proportion of interbedded clay and silt. The deposit has a shape and a mineralogical zoning characteristic of roll-front deposits. The oxidised sand is yellow and orange from abundant limonite, whereas the reduced sand is grey and contains pyrite. Pyrite is also relatively abundant in the ore zone. Carbon, mostly as organic plant matter, remains in the unoxidised zones.

The ore consists of microscopic coffinite associated with the clayey humic and pyritic matrix of a porous sandstone with interbedded clay and silt.

Mines Administration Pty Ltd proposed to extract the uranium by solution mining. Using parameters for resource calculations applicable to this type of extraction, the company estimated that the in-situ probable resources amount to 2 159 000 t of ore averaging 0.157% U_3O_8. This represents 3390 t of contained U_3O_8 (Mines Administration Pty Ltd, 1981).

Other deposits

The **East Kalkaroo** deposit is 2.5 km east of Honeymoon, and occurs along the outer edge of the same bend in the Yarramba Channel. Sedimentary Uranium NL (1981) stated that the inferred resources amount to 1000 t of contained U_3O_8 with an average grade of 0.14% U_3O_8.

Mineralisation is continuous between the Honeymoon and East Kalkaroo deposits, and Minad, Teton, and CEC formed a joint venture with Sedimentary Uranium to test the mineralised zone between these deposits. Drilling in 1980 and 1981 outlined a zone of higher-grade mineralisation measuring 1400 m by 200 m (Sedimentary Uranium NL, 1981), but resources have not been published.

The **Yarramba** deposit is in the Yarramba Channel, 12 km north of Honeymoon. The ore forms sub-parallel lenses along the upper and lower limits of the oxidised zone. No roll-front has been found. The deposit is small, and reserves have not been published (Brunt, 1978).

Gould's Dam deposit is in the Billeroo Channel (Ellis, 1980). It contains 1100 t U_3O_8 classified as in-situ possible resources (CSR Ltd, 1982).

The **Paralana–Pepegoona** area is about 5 km west of the Beverley deposit. Tertiary palaeochannel sediments in this area are close to the edge of the Mount Painter Complex. Drilling carried out by Exoil NL, Transoil NL, Petromin NL, and various other joint-venture partners established in-situ resources in several palaeochannels amounting to 1000 t U_3O_8 with an average grade of 0.2% U_3O_8 (South Australia Department of Mines & Energy, 1983a).

Westmoreland–Pandanus Creek uranium field

The Westmoreland deposits are in northwest Queensland, 400 km north-northwest of Mount Isa, in an area contiguous with the Pandanus Creek area in the Northern Territory (Fig. 21). R.T. Norris, a prospector, discovered uranium at Pandanus Creek in 1955. The next year, his niece, Eva Clarke, discovered the main deposit at Pandanus Creek — later named the Eva deposit (Morgan, 1965; Lord, 1955). The Cobar 2 deposit, found by A.R. Blackwell in 1956, is 20 km north-northeast of the Pandanus Creek deposit. El Hussen, 5 km southwest of Cobar 2, is another uranium prospect discovered in the mid fifties.

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

The next exploration phase was in 1967–75 when Queensland Mines Ltd undertook a major exploration and drilling program for stratabound deposits in the Westmoreland Conglomerate. The company delineated the Jack, Garee, and Langi deposits near the Redtree No. 1 lease (Fig. 22). The emphasis of exploration shifted to northeast-trending structures when high-grade uranium mineralisation was located along the Redtree joint zone to the east of Redtree No. 1 lease. However, the high-grade mineralisation was later found to be discontinuous, and earlier resource estimates were substantially reduced (Fuchs & Schindlmayr, 1981). Exploration continued in the Westmoreland area from 1976 to 1982. A joint venture operated by Urangesellschaft Australia Pty Ltd located the Junnagunna and Sue deposits and delineated the Outcamp deposit.

On the Northern Territory side of the border exploration by Kratos Uranium NL, during 1976–1982, located uranium mineralisation on a northeast-trending fault structure.

Regional geological setting

The field (Fig. 21) is near the southeastern margin of the Middle Proterozoic (Carpentarian) McArthur Basin, where it laps to the south onto the Early–Middle Proterozoic basement rocks of the Murphy Inlier. The oldest rock unit in the Inlier is Early Proterozoic schist (Murphy Metamorphics), but most of the outcrop in Queensland comprises Early–Middle Proterozoic acid lava and ignimbrite (Cliffdale Volcanics). The younger units of the Cliffdale Volcanics have been dated at 1770 Ma. Multiphase intrusions of the Nicholson Granite Complex cut both schists and volcanics (Grimes & Sweet, 1979; Sweet, Mock, & Mitchell, 1981; Plumb, Derrick, & Wilson, 1980).

The Murphy Inlier trends east-northeast and its northern flank is unconformably overlain by gently tilted sedimentary and volcanic rocks of the Tawallah Group (McArthur Basin). The basal unit, the Westmoreland Conglomerate, is a fluvial deposit over 1200 m thick. The basic Seigal Volcanics overlie the Westmoreland Conglomerate, and are followed by dolomite, sandstone, and basic and acid volcanics of the upper part of the Tawallah Group.

The Pandanus Creek deposit is in altered volcanics of the Murphy Inlier. The Westmoreland uranium deposits occur in the vicinity of fault and joint zones, commonly intruded by basic to intermediate dykes, in the uppermost sandstone member of the Westmoreland Conglomerate. The uranium at Cobar 2 and El Hussen is in faults and shears in the Seigal Volcanics near their contact with the underlying Westmoreland Conglomerate.

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

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

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

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

Deposits

Although most of the known uranium resources are in the Westmoreland area, all production in this field has come from the small Pandanus Creek and Cobar 2 deposits.

The Broken Hill Proprietary Co. Ltd delineated the **Pandanus Creek** deposit in 1958–59 and South Alligator Uranium NL mined it from 1960–1962. Drilling indicated 55 000 t of

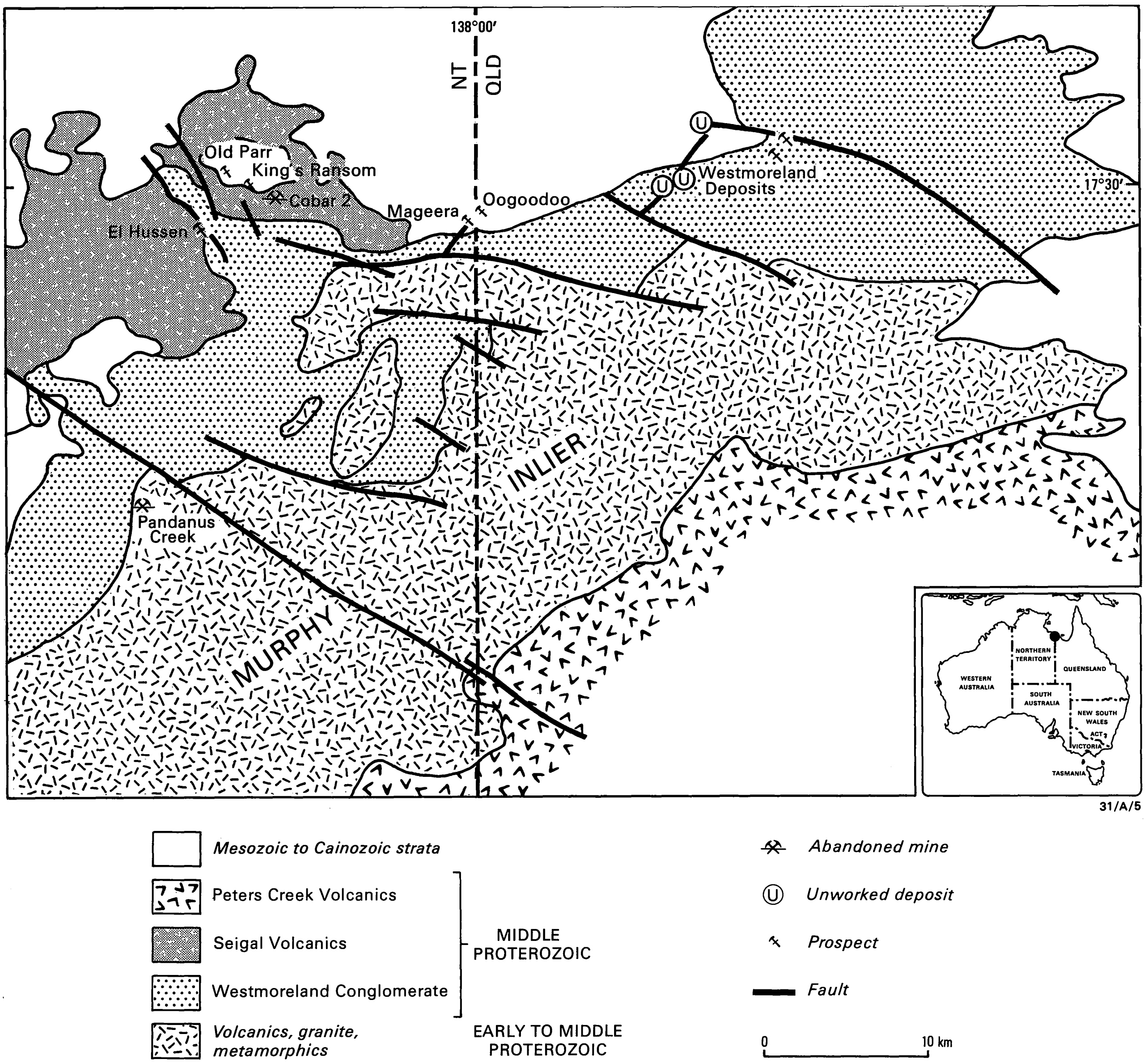


Fig. 21. Simplified geological map, Westmoreland–Pandanus Creek uranium field, NT & Qld.

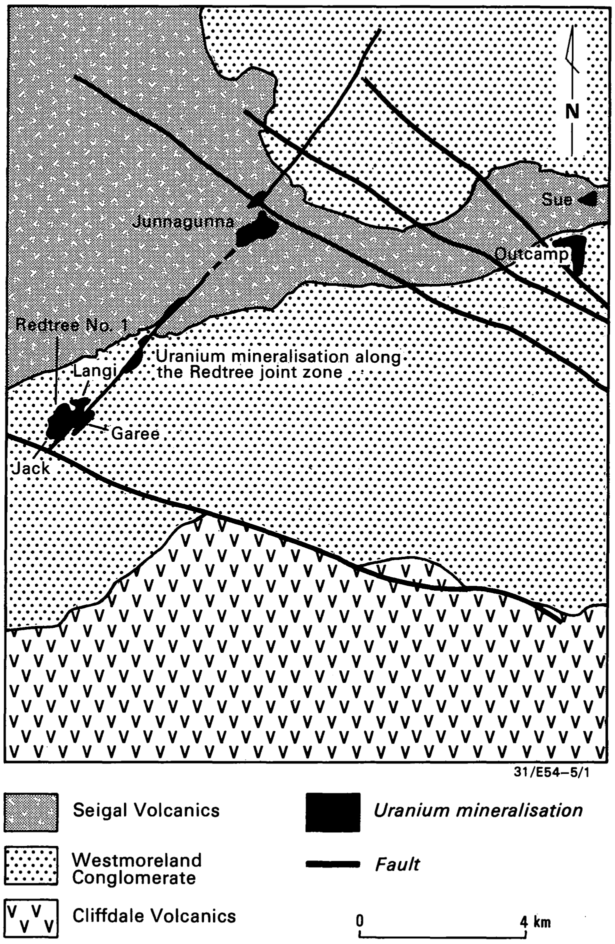


Fig. 22. Geology of the Westmoreland uranium deposits (after Fuchs & Schindlmayr, 1981).

ore averaging 0.56% U_3O_8 to a depth of 42 m. Selective mining to a depth of 25 m produced 312 t of high-grade ore averaging 8.37% U_3O_8, which was trucked 1850 km to the treatment plant at Rum Jungle. A spoil dump near the mine contains about 3000 t of material averaging over 1% U_3O_8 (Morgan, 1965; Morgan & Campi, 1986). The deposits occur in en-echelon shear zones up to 2 m wide which strike north-northeast and dip northwest. The host rocks are bleached, intensely altered acid volcanics (Cliffdale Volcanics) overlain by sandstone of the Westmoreland Conglomerate. The orebody is within the contact aureole of a small stock of granite which crops out only 15 m to the west of the margin of the orebody. The ore shoots plunge to the north-northeast, parallel to the granite contact, but no uranium mineralisation has been found in the granite (Sweet & others, 1981; Morgan, 1965; Webb, 1976; Morgan & Campi, 1986). The youngest granite intruding the host rocks has been dated at approximately 1773 Ma, whereas the uranium mineralisation is dated at 850 Ma. It is unlikely therefore that the orebody was formed by hydrothermal solutions emanating from the granite. Instead, Morgan & Campi (1986) have proposed a hydrothermal origin from solutions ascending along major faults during tectonism. The bulk of the ore is in a band of sericitic quartzite within porphyritic lava. The main ore minerals are pitchblende, gummite, uranophane, and sklodowskite. The ore also contains significant amounts of gold and silver.

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

Other prospects in the Pandanus Creek area include **King's Ransom, Old Parr, El Hussen, Mageera,** and **Oogoodoo.** The first two are in shears in the Seigal Volcanics about 4 km northeast and east-northeast of El Hussen respectively. At El Hussen uranium occurs in shears in the volcanics and also along the sheared contact with the Westmoreland Conglomerate (Sweet & others, 1981). The Mageera and Oogoodoo prospects are close to a northeast-trending fault, in which the uranium is near the Westmoreland Conglomerate/Seigal Volcanics contact (Kratos Uranium NL, 1982).

In the Westmoreland area most of the deposits are flat-lying lenses flanking the northeast-trending Redtree joint zone (Fig. 22). Basic dykes are emplaced along the joint zone, which is about 8 km long (the southern part of the joint zone is known as the Namalangi section, and the northern part the Huarabagoo section). Uranium mineralisation occurs either as:

— 'horizontal mineralisation' (Fuchs & Schindlmayr, 1981), subparallel either to the contact of the overlying Seigal Volcanics or parallel to intermediate sills in the uppermost units of the Westmoreland Conglomerate, or

— 'vertical mineralisation' as steeply dipping lenses next to and within the Redtree dyke (Fig. 23).

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

The **Redtree No. 1** lease (MIM) covers the northeastern part of what is now known as the **Jack** deposit. It is a horizontal-type deposit in sandstone on the northwest side of the Redtree joint zone. Torbernite, metatorbernite, and carnotite are the main ore minerals, and the deposit is about 6 m thick and 6 to 20 m below the surface. Closer to the Redtree joint zone, the deposit grades into discontinuous vertical lenses of primary uranium mineralisation. The horizontal-type **Langi** deposit is some 600 m northeast of the Jack deposit.

The **Garee** deposit, southeast of the Redtree joint zone, is a flat-dipping tabular body in sandstone; its average thickness is 9 m and it is 6 to 20 m below surface. Mineralisation is mainly pitchblende, with minor in-situ oxidation at its eastern end.

The **Junnagunna** deposit is 7.5 km northeast of the Jack deposit and occurs as horizontal mineralisation in sandstone, of the Westmoreland Conglomerate. It is covered by soil and also by the Seigal Volcanics. This deposit was discovered by drilling on radon anomalies.

The **Outcamp** and **Sue** deposits are located away from the Redtree joint zone, 8 km east of the Junnagunna deposit.

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

It was originally thought that the vertical-type mineralisation in the Redtree joint zone had much more potential than the horizontal deposits near the joint zone. Later these vertical lenses were found to be discontinuous and the substantial resource tonnages attributed at first to the vertical lenses could not be sustained (Queensland Mines Ltd, 1973; Fuchs &

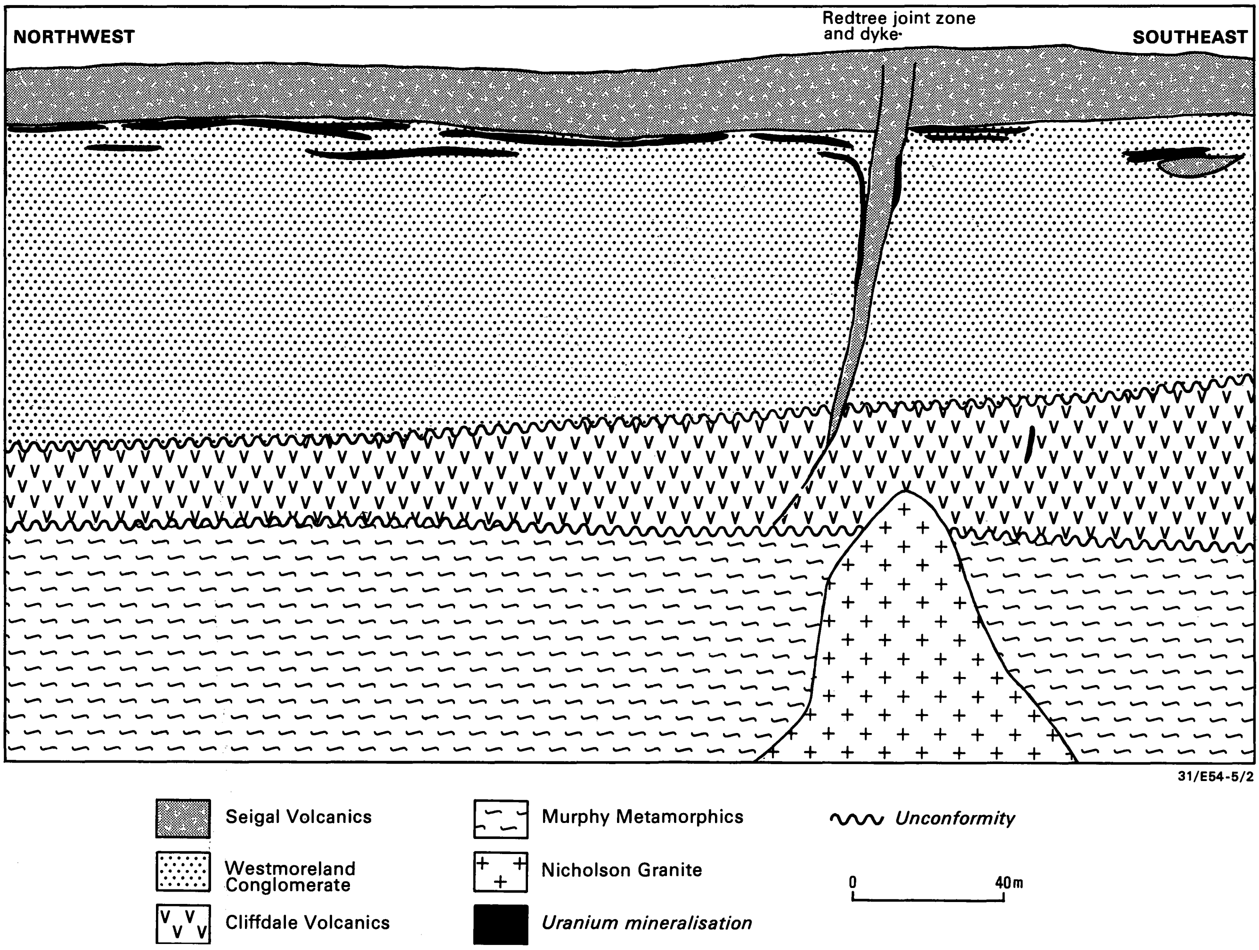


Fig. 23. Diagrammatic cross-section of uranium deposits in the Westmoreland area (after Fuchs & Schindlmayr, 1981).

Schindlmayr, 1981). The bulk of the known uranium resource is contained in the stratabound horizontal deposits. The latest available published estimates are shown in Table 11 (Fuchs & Schindlmayr, 1981).

CSR Ltd (1982) published the uranium resources for all the Westmoreland deposits as 3722 t U_3O_8 in proved ore, 3515 t U_3O_8 in probable ore, and 4787 t U_3O_8 in possible resource.

Table 11. Resources of the main deposits in the Westmoreland–Pandanus Creek uranium field

	% U_3O_8	t, U_3O_8
Redtree No. 1 Lease	0.115	1630
Jack	0.16	1405
Garee	0.18	1500
Langi	0.12	110
Junnagunna	0.14	3870
Sue	0.11	675
Outcamp	0.085	945

Ngalia Basin

Uranium mineralisation was discovered in the Ngalia Basin (NT) in 1970 when a prospector employed by Central Pacific Minerals NL found radioactive gossanous material in a quartz vein in granite. This prospect was later named Rankins Reward. Further ground prospecting located carnotite in outcrops of the Mount Eclipse Sandstone and several prospects were discovered along the northern outcrops of this unit (Fig. 24) (Ivanac & Spark, 1976).

In 1973, uranium mineralisation was discovered in Quaternary and Recent calcrete in the southern part of the basin.

Regional geological setting

The Ngalia Basin is an elongate, intracratonic downwarp filled by Late Proterozoic and Palaeozoic strata. The basement rocks are highly deformed metamorphics, granites, and sediments of the Early to Middle Proterozoic Arunta Block.

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

The uranium is in the lower part of the Late Devonian to Late Carboniferous Mount Eclipse Sandstone (Ivanac & Spark, 1976). The host rocks are kaolinised white, grey, and reddish-brown arkosic sandstone and feldspathic sandstone with minor shale, siltstone, conglomerate, and dolomite interbeds. The sandstone along the northern margin of the basin is thrust-faulted and folded.

Carnotite is the main ore mineral in the weathered sandstone and uraninite in the primary zone. Carbonacous material including plant remains is common in the sandstone.

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

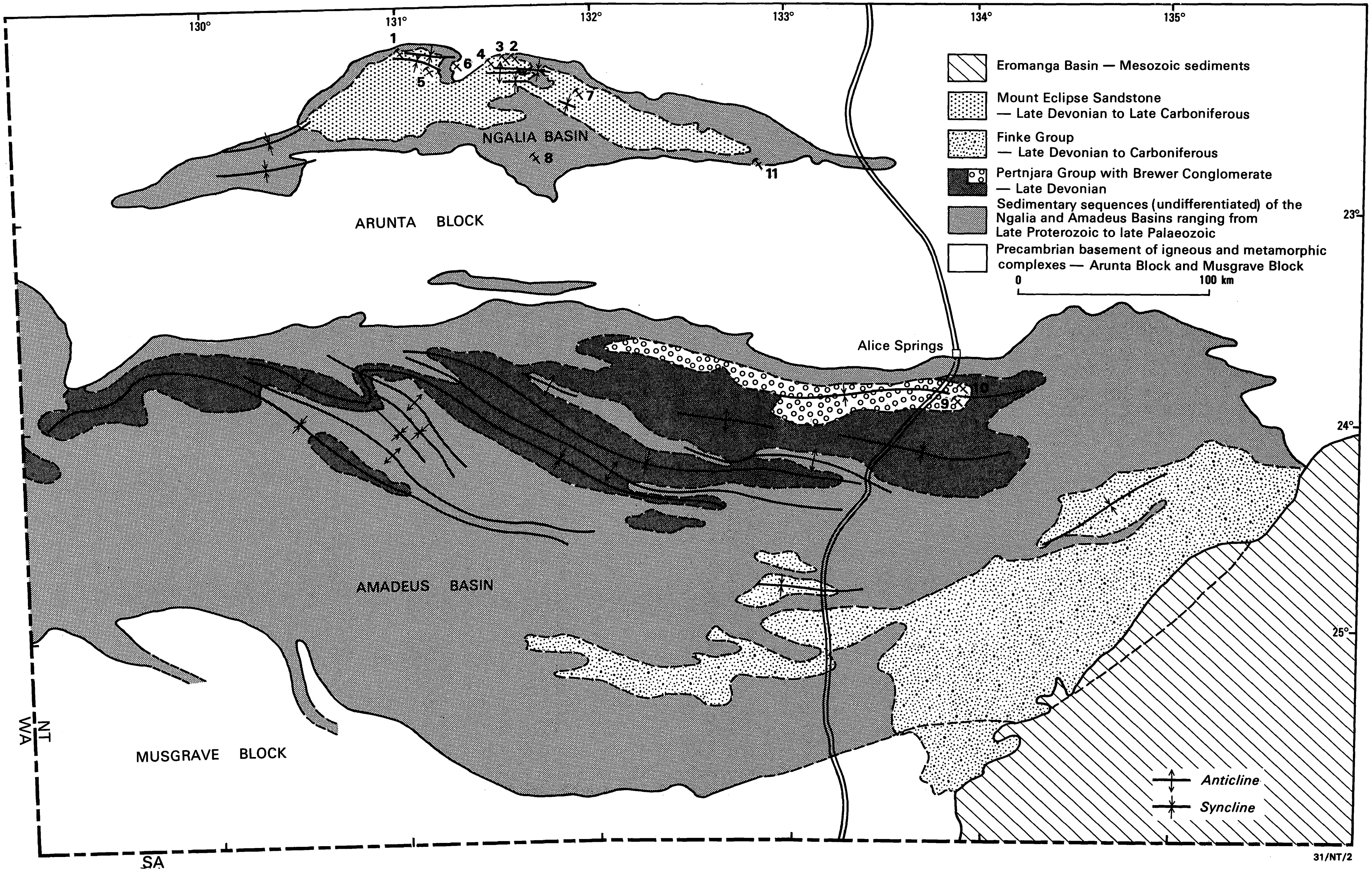


Fig. 24. Simplified geology, Ngalia and Amadeus Basins, NT, showing the Mount Eclipse Sandstone, Pertnjara Group, Finke Group, and principal uranium prospects: 1 Bigrlyi, 2 Walbiri, 3 Sunberg, 4 Coonega, 5 Dingo's Rest, 6 Rankin's Reward, 7 Karin, 8 Currinya, 9 Angela, 10 Pamela, 11 Napperby.

Bigrlyi deposit

This deposit is a series of discontinuous lenses that crop out over a strike length of 12.5 km in the lower part of the Mount Eclipse Sandstone along the northern margin of the Ngalia Basin (Ivanac & Spark, 1976; Wells & Moss, 1983). Sixteen surface carnotite prospects have been located. The host rock is a hard, medium-to-coarse arkosic sandstone, kaolinised in places and containing plant remains and other carbonaceous material. The sandstone sequence is tightly folded and dips vary from 75°S to 80°N (overturned). Detailed drilling has outlined ore resources in eight separate lenses. Central Pacific Minerals NL (1982) reported total resources as: proved — 2181 t of contained U_3O_8 averaging 0.372%; probable — 486 t of contained U_3O_8 averaging 0.252%; and possible — 107 t of contained U_3O_8 averaging 0.361%.

Walbiri deposit

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

Other deposits

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

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

Amadeus Basin

A regional airborne radiometric survey over Palaeozoic sandstone of the Amadeus Basin was carried out by Uranerz Australia Pty Ltd. During 1973 and 1974, costeaning and drilling of these anomalies resulted in the discovery of the Angela and Pamela prospects in the Late Devonian Undandita Member (sandstone) in the upper part of the Brewer conglomerate. The project is a joint venture between Uranerz Australia Pty Ltd and Carpentaria Exploration Co. Pty Ltd, a wholly owned subsidiary of MIM Holdings Ltd.

Regional geological setting

The regional geology of the intracratonic Amadeus Basin (Fig. 24) has been described in detail by Wells, Ranford, Stewart, Cook, & Shaw (1967); Wells, Forman, Ranford, & Cook (1970); and Shaw & Wells (1983). Its strata range in age from Late Proterozoic to Carboniferous. Several major episodes of sedimentation followed major phases of uplift of the Arunta Block along the northern margin. Late Devonian terrestrial sediments, 3100 m thick, comprise proximal alluvial-fan conglomerate facies (Brewer Conglomerate) grading south and southeast into a braided-stream facies and playa-lake siltstone facies (Horseshoe Bend Shale) (Jones, 1983).

The Brewer Conglomerate is an upper unit of the Pertnjara Group, a thick Late Devonian sequence of continental shale, sandstone, and conglomerate. The Undandita Member comprises pebbly sandstone, and minor siltstone and conglomerate which contains clasts of quartzite, sandstone, and crystalline rocks (Shaw & Wells, 1983).

The Pertnjara Group sandstone and conglomerate are time-equivalents of the Mount Eclipse Sandstone in the Ngalia Basin.

Angela and Pamela deposits

These deposits are in the Late Devonian Undandita Member sandstone, about 28 km south of Alice Springs (Fig. 24). The Undandita Member is exposed in the broad regional east-west-trending Missionary Syncline.

Groundwater is thought to have entered the Brewer Conglomerate along the northern edge of the basin and migrated south carrying dissolved uranium which was precipitated when it encountered reducing facies in sandstone. The host sandstone was deposited by braided streams; hence the amount of interbedded shale is relatively small and the stream channels ill-defined. The redox boundary forms an irregular interdigitation of oxidised and reduced facies with local small uranium concentrations (Jones, 1983).

MIM Holdings Ltd (1980) reported that the total in-situ resources (both indicated and inferred) amount to 7700 t of contained U_3O_8.

Officer Basin

In 1978, PNC Exploration (Australia) Pty Ltd (PNC) used widely spaced reconnaissance drilling to explore for sandstone-type deposits in the southwestern part of the Late Proterozoic to Cretaceous Officer Basin, WA. Uranium was intersected in Tertiary sediments in an embayment along the basin margin. Drilling between 1978 and 1982 defined several ore-grade bodies called collectively the Mulga Rock deposit (initially known as the Officer Basin prospect). It is 250 km east-northeast of Kalgoorlie (Fig. 16) and 40 km southeast of the eastern edge of Lake Minigwal. The mineralisation does not crop out and in 1983 a large 30-m-deep costean was dug and large samples of higher-grade material were collected for metallurgical tests.

Regional geological setting

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

The Mulga Rock deposit occurs in Tertiary interbedded sand and peat, in an embayment along the southwestern margin of the Officer Basin. Archaean basement rocks of the Yilgarn Block and Proterozoic rocks of the Albany-Fraser Province form the western and southern margins of the embayment; they comprise granite, migmatite, and granite gneiss together with greenstone belts which contain amphibolite, ultramafics, schist, and banded iron formation. To the east are flat-lying Cretaceous and Tertiary strata of the Eucla Basin, which overlies the Officer Basin and interfingers with its upper units.

In the southwest of the Officer Basin the oldest unit is the Early Permian Paterson Formation, consisting of well-bedded mudstone, siltstone, and minor coarse sandstone, and conglomerate (including tillite) (Bunting & van de Graaff, 1977). The overlying Cretaceous and Tertiary sediments are a thin sequence of shallow-water sediments. They comprise sandstone, calcarenite, siltstone, claystone, and peat mainly derived from Archaean granite and migmatite of the Yilgarn Block.

Mulga Rock deposit

The uranium occurs in carbonaceous sand and peat in a broad palaeochannel cut into mudstone, siltstone, and tillite of the Paterson Formation, mainly along a redox boundary near the present water-table.

PNC has not announced resource estimates but an estimate of 10 000 t of contained U_3O_8 in situ was published in the *Australian Financial Review* of 15 June 1981, based on Japanese media reports.

Carnarvon Basin

Minatome Australia Pty Ltd explored Proterozoic rocks of the Gascoyne Block, WA (Fig. 16) from 1972–1975 and established that the Proterozoic granites in the area are enriched in leachable uranium. Water bores were sampled and analysed and it was established that groundwater from Cretaceous and Cainozoic strata of the Peedamullah Shelf of the Carnarvon Basin contains significant amounts of uranium.

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

Regional geological setting

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

The basement rocks are Archaean(?) to Middle Proterozoic metasediments and granite.

There is a major unconformity between the Proterozoic basement and the Carnarvon Basin shelf strata. Basal terrestrial conglomerate in depressions and channels is succeeded by other formations which transgress basement to the east. The Cretaceous, shallow-water-marine Birdrong Sandstone overlies the conglomerate and in turn is overlain by marine shale and radiolarite. The uranium is in sandstone units in the palaeochannels.

Cainozoic calcareous siltstone, clay, and gravel overlie the Cretaceous strata with an erosional hiatus and infill topographic lows in the Precambrian shield.

Manyingee deposit

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

- Windalia Radiolarite; averages 2 m thick and conformably overlies the Muderong Shale.
- Muderong Shale; fine-grained glauconitic shale conformably overlying Birdrong Sandstone.
- Birdrong Sandstone; conformably overlies the conglomerate. The Birdrong Sandstone is less than 50 m thick and the main rock types in the mineralised areas are:
  - poorly sorted coarse and medium-grained feldspathic sandstone; clasts include lithic fragments, muscovite, wood, and lignite;
  - well-sorted quartz sandstone, rich in pyrite;
  - greenish siltstone and claystone.
- conglomerate (unnamed); discontinuous; occurs only in the channel; average about 60 m thick; rests unconformably/disconformably on arkose; polymictic; clasts well-rounded.
- arkose (unnamed); consists of angular granitic fragments

The uranium is in the lower part of the Birdrong Sandstone, and is associated with intense oxidation of the originally reduced sediments by groundwater moving along the palaeochannels. The groundwater contained soluble uranium that was precipitated in the transition zone between oxidised and reduced sediments to form layers and roll-front deposits.

The permeability of the individual rock units controlled the migration of groundwater and the deposition of uranium. Uranium precipitated where the sandstone was less permeable, at features such as channel banks, bends, or bars.

The main minerals in the lenses and roll-fronts are uraninite, coffinite, and minor pyrite together with their oxidised counterparts, phosphuranylite, meta-autunite, and associated siderite and limonite.

Resource estimates have not been reported. Valsardieu & others (1981) stated that detailed drilling has defined two areas of high-grade mineralisation — Manyingee 1 and Manyingee 2. Manyingee 1 is 1500 m long and 300–1000 m wide. High-grade mineralisation forms discontinuous lenses and roll-fronts within a 40-m-thick zone in the Birdrong Sandstone and the underlying conglomerate. The Manyingee 2 deposit is 500 m long and up to 300 m wide. Mineralised lenses occur within a zone 50 m thick.

Canning Basin

From 1978–83, Afmeco Pty Ltd explored for sandstone-type deposits along the northern edge of the Canning Basin, in the north of Western Australia. The area was selected partly because the sedimentary strata have been derived from erosion of the Halls Creek–King Leopold Mobile Zone which contains high levels of background uranium and several small uranium occurrences. Interpretation of Landsat imagery and data from petroleum exploration wells were used in conjunction with available regional, geological maps to define the broad extent of Palaeozoic and Tertiary sandstone sequences, and their stratigraphy. Initial reconnaissance was followed by a major program of detailed exploration and stratigraphic drilling in five main areas (Botten, 1984).

Areas of interest were investigated in detail by airborne geophysical surveys (magnetic and radiometric), gravity surveys, hydrogeological studies, detailed drilling, and down-hole geophysical surveys. To the end of 1983, a total of 57 000 m of reverse-circulation 'aircore' and diamond drilling had been completed. The maximum depth of drilling was 250–300 m (Botten, 1984).

Regional geological setting

The regional geology of the area has been described by Veevers & Wells (1961), Forman & Wales (1981), and Towner & Gibson (1983).

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

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

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

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

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

Oobagooma deposit

The Oobagooma deposit (Fig. 16) is in the Yampi Sandstone in the Yampi embayment. No tonnage and grade have been reported by Afmeco.

The Yampi embayment trends southeast and is flanked by Archaean(?) and Proterozoic basement. The margins are controlled by regional faults. The sequence in the embayment is

			Thickness
(top)	— younger sediments		up to 20 m
	— Grant Formation (sandstone, siltstone)	Late Carboniferous — Early Permian	up to 200 m
	— Yampi Sandstone Formation (sandstone, siltstone)	Late Devonian–Early Carboniferous	60–150 m
(base)	— Lillybooroora Conglomerate	Late Devonian	greater than 50 m

The Lillybooroora Conglomerate consists of quartzite pebbles and cobbles derived from Proterozoic King Leopold Formation in a matrix of soft, clay-rich sand. The Yampi Sandstone consists of interbedded deltaic sandstone and siltstone. The Grant Group — also interbedded sandstone and siltstone — unconformably overlies the Yampi Sandstone.

Groundwater has migrated along the palaeochannel and formed a broad tongue of oxidised sandstone. Uranium mineralisation was precipitated in and around concentrations of detrital organic matter, and is now encountered at depths of 60–130 m.

Eyre Peninsula region

In the northwest, uranium occurs in Eocene palaeochannel sediment overlying Archaean and Proterozoic granite, gneiss, and volcanics of the Gawler Craton. Extensive zones of low-grade mineralisation are known in the Malbooma area and Wynbring area. Further south, mineralisation is known in the Narlaby and Yaninee palaeochannels (Fig. 17).

In the **Malbooma** area, 80 km west of Tarcoola, PNC carried out a major drilling program from 1973–1982 that outlined zones of mineralisation in Eocene lignitic strata at a depth of 30 m. PNC estimated they had outlined an indicated resource of 4000 t of contained U_3O_8 with an average grade of 0.034% U_3O_8 and average thickness of 1.5 m (South Australia Department of Mines & Energy, 1982a).

In the **Wynbring** area, further west, PNC reported that uranium occurs in Tertiary palaeochannel sediment overlying Archaean gneiss and granite. The Wynbring channel is 1.4 to 3 km wide and contains up to 74 m of coarse to fine sand with lignite, mudstone, and siltstone interbeds. Significant uranium mineralisation coincides with the level of the present water table (less than 20 m depth) in sand and interbedded lignite (South Australia Department of Mines & Energy, 1983).

From 1979 to 1982 Carpentaria Exploration Co. Pty Ltd explored Eocene palaeochannel sediments in the northern Eyre Peninsula. The **Narlaby and Yaninee palaeochannels** were defined (Binks & Hooper, 1984). Proterozoic granitic rocks of the Hiltaba Granite and Lincoln Complex form the basement into which these channels were eroded. The Hiltaba Granite has a relatively high uranium content (averaging 7 ppm U) and is believed to be the source of the mineralisation. The Narlaby palaeochannel is about 170 km long and up to 10 km wide, and traverses the northwest-trending Corrobinnie Depression. The smaller Yaninee palaeochannel flows south from Minnipa (Binks & Hooper, 1984; SADME, March 1984). The mineralised strata are fine-grained sand and gravel with interbedded clay. In the reduced state the sand is grey to black with variable humic staining, carbonaceous material, and minor pyrite; in the oxidised state it is pink to pale-brown. The Eocene section is up to 80 m thick and is overlain by up to 100 m of younger sediment. In the western part of the Narlaby palaeochannel, low-grade uranium mineralisation is associated with redox fronts. Average grades in this western part of the Narlaby palaeochannel are from 100–200 ppm eU_3O_8 ('equivalent U_3O_8', from radiometric measurements) and this mineralisation extends over more than 3 km². The mineralisation is uneconomic (Binks & Hooper, 1984).

Other prospects

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

Mesozoic sandstones in the **Carpentaria Basin** and **northwestern Eromanga Basin** overlie the eastern and southern margins of the Mount Isa Block. They were derived from Middle Proterozoic metasediments and granite and are considered prospective. PNC tested the sandstone in the **Boulia Shelf** south of Mount Isa (McKay, 1982; Dunn, 1983). The thin Mesozoic and Cainozoic strata overlie both the Proterozoic metasediments of the Mount Isa Block and the Cambrian–Ordovician sedimentary rocks of the Georgina Basin. Reconnaissance percussion drilling defined the Mesozoic Binfield palaeochannel in the Burke River area, 75 km north of Boulia. It contains fluvial sandstone and carbonaceous pelite of the Longsight Sandstone and Wilgunya Formation (Cretaceous). A redox boundary was outlined, but only very-low-grade mineralisation was intersected. Areas in the Carpentaria Basin have also been tested. The Eulo Queen Group (Jurassic) and Gilbert River Formation (Early Cretaceous) are also considered favourable hosts (Brunt, 1972). Sandstone of the Gilbert River Formation was drilled in areas where it overlies the eastern edge of the Mount Isa Block. Low-grade mineralisation was intersected in sandstone (containing carbonaceous matter and pyrite) in the Glen Isla and Malakoff areas, 15 km east of Quamby (Mines Administration Pty Ltd, 1980) (Fig. 25).

In the **Gilberton Basin** there are zones of low-grade mineralisation in reduced sandstone of the Gilberton Formation (Late Devonian), 350 km west of Townsville, Qld (Fig. 27) (Bain & Withnall, 1984).

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

SURFICIAL DEPOSITS

Calcrete deposits of the Yilgarn Block

Exploration of the Tertiary Yilgarn drainage courses passed through a number of phases (Carter, 1981). Secondary uranium-vanadium ochre was found in 1953 in surficial deposits at Lake Dundas, a few kilometres south of Norseman. Carnotite in calcrete was found about 20 km southeast of Mundong Well during an investigation in 1961 of airborne radiometric anomalies delineated by a BMR survey (Gardner & Jones, 1967). It was not until the late 1960s that exploration was directed towards the drainages. In 1971, carnotite was recognised in calcrete a few kilometres north of Yamarna new homestead and this resulted in some exploration activity over calcrete deposits. In January 1972 Western Mining Corporation Ltd (WMC) announced the discovery of the large Yeelirrie deposit (found in 1970), and exploration for calcrete uranium deposits became very active.

Before the discovery of Yeelirrie, WMC was investigating the potential of the valley-fill sediment as host to sandstone-type deposits (Duncan & Levy, 1981). A BMR airborne radiometric survey (Gerdes & others, 1970) showed an anomaly near Yeelirrie aligned along a Tertiary drainage channel. WMC considered this alignment significant, and investigated the anomaly by detailed ground radiometrics. Drilling then delineated the deposit.

Regional geological setting

Carnotite mineralisation is widespread in calcreted trunk valleys of the Tertiary drainage systems that developed over 400 000 km^2 of southwestern Australia. However, known calcrete uranium deposits and significant prospects are confined to the granitic and greenstone terrane comprising the northern part of the Archaean Yilgarn Block (Fig. 16). Anomalous uranium concentrations in calcreted drainage channels also extend north of the Yilgarn block, over the Proterozoic Gascoyne Block and Bangemall Basin, the Archaean Pilbara Block, and parts of South Australia and the Northern Territory (Butt, Mann, & Horwitz, 1984). The western and northwestern limit of known significant concentrations of surficial uranium mineralisation is defined by an area of active erosion by streams draining to the coast. This is known as the 'Meckering line' (Butt, Horwitz, & Mann, 1977). The southern limit of known calcrete uranium deposits and significant prospects, known as the 'Menzies line', at about latitude 29°S, is defined by a number of interrelated geochemical and climatic characteristics.

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

Butt & others (1977) catalogued 62 calcrete uranium occurrences, and Carter (1981) also included a listing of localities investigated for calcrete uranium mineralisation. Butt & others (1984) classified the main uranium deposits according to their geomorphological characteristics into three main types.

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

Yeelirrie deposit

The Yeelirrie deposit, 650 km northeast of Perth, is in the central drainage channel of a wide, flat valley in a granitoid gneiss terrane in the northeastern Yilgarn Block (Fig. 16). The maximum thickness of fill in the Yeelirrie channel exceeds 85 m, although near the orebody it is seldom more than 30 m.

Carnotite forms thin films on cavity walls in porcellanous calcrete, dispersions through earthy calcrete, and grain coatings and disseminations in quartzose clay ('clay quartz').

The orebody measures 9000 m by an average of 750 m (maximum width 1500 m). The bulk of the ore occurs in a more or less continuous horizontal zone having an irregularly lenticular cross-section centred about 5.5 m below the surface and 1 m below the water table. The average thickness of mineralised material assaying 0.10% U_3O_8 or greater is 3 m and the maximum thickness 7 m (Western Mining Corporation Ltd (WMC), 1978).

In profile through the valley fill at the orebody, three main lithological units are identified (Cameron, 1984) — overburden, calcrete, and a clay-quartz horizon (combined thickness about 30 m).

The overburden (1–2 m thick) of sandy, friable grey-brown soil is locally indurated by silica and passes down into carbonated loam.

Two types of calcrete are present within the calcrete layer — one is buff, friable, earthy and the other is white, hard, nodular, and porcellanous and is commonly riddled with voids. The earthy calcrete forms a fairly continuous layer which grades upwards into the overlying soils. The porcellanous calcrete forms discrete spheres which coalesce in places to form bulbous masses and commonly truncate the horizontal layering of the earthy calcrete.

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

In the Draft Environmental Impact Statement, WMC noted that 90% of the mineralisation is in a zone 5 m thick at the transition between the calcrete and the clay-quartz. The core of the orebody contains 37 094 t of U_3O_8 averaging 0.17%, and successive envelopes contain 5108 t of U_3O_8 at 0.09%, and 4693 t of U_3O_8 at 0.07%, for a total of 46 895 t of U_3O_8 at 0.14% (Western Mining Corporation, 1978). In their 1982 Annual Report, WMC announced that further drilling had increased the ore reserves. The proved reserves were stated to be 32 000 t of U_3O_8 in prime ore (+ 0.15% U_3O_8) averaging 0.24% U_3O_8 and 20 500 t of U_3O_8 in intermediate ore (0.05% to 0.15% U_3O_8) averaging 0.09% U_3O_8. Total proved ore reserves are 52 500 t of U_3O_8 at 0.15%.

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

Lake Way deposit

The Lake Way deposit is at the northeastern margin of Lake Way, a playa, 17 km southeast of Wiluna and 740 km northeast of Perth. The deposit was discovered in 1972, and, by 1977, drilling and sampling were considered to have defined a deposit large enough to warrant metallurgical evaluation.

The mineralisation is in earthy calcrete and clay in the lower reaches of the Uramurdah drainage where it enters the northeast margin of Lake Way. Carnotite occurs on slickenside surfaces, on bedding planes, in clay-gravel, and as coatings on broken calcrete blocks at the water table/air interface, extending up to 1 m above the interface and down to 2 m below (Brian Lancaster & Associates, 1981). There are four areas of ore-grade mineralisation connected by areas of subeconomic mineralisation. The thickness of the mineralisation averages 1.5 m and varies from a maximum of 5 m down to a few centimetres. French & Allen (1984) stated that reserves at a cut-off grade of 0.029% U_3O_8 amounted to 5200 t of U_3O_8 or 3300 t of U_3O_8 at a cut-off of 0.065% U_3O_8. Six target areas remain to be drilled. Planned production is by open-cut mining and treatment of ore by alkaline leaching, followed by resin-in-pulp ion-exchange, to produce 500 t U_3O_8/year.

Other deposits

Cultus Pacific NL (1979) estimated the resource potential of four other calcrete deposits in the Yilgarn Block, as follows:

Thatcher Soak	— 4100 t U_3O_8,	average grade 0.03%
Lake Mason	— 2700 t U_3O_8,	average grade 0.035%
Lake Raeside	— 1700 t U_3O_8,	average grade 0.025%
Lake Maitland	— 500 t U_3O_8,	average grade 0.04%

At **Thatcher Soak** the mineralisation extends over a length of 7.5 km. It is 100–200 m wide and up to 2 m thick, and covered by shallow overburden averaging 1–2 m thick. The best ore sample analysis was 0.06% U_3O_8 over 2 m.

At **Lake Mason** the mineralised area is 4.9 km long and 250–750 m wide. The average thickness is less than 1 m covered by an overburden of 1–2 m. The best analysis was 0.08% U_3O_8 over 2 m.

At **Lake Maitland** exploration has revealed two small zones of mineralisation. The best analysis was 0.06% U_3O_8 over 2 m.

Cavaney (1984) described a **second** surficial carnotite **deposit at Lake Maitland** held by MIM Holdings Ltd. Mineralisation enclosed by the 0.025% U_3O_8 contour extends in an arcuate zone (within a playa) some 6 km by 0.3–0.5 km. Uranium content is mostly less than 0.07% U_3O_8, but peak values exceed 0.18%. The carnotite is mostly in slabby calcrete, but also in sand, clay, and silt. The ore resources within the Lake Maitland deposit held by MIM Holdings Ltd were estimated to be 3500 t of U_3O_8 (MIM Holdings Ltd, 1980).

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

At **Lake Austin** the carnotite mineralisation is in a narrow arm of a playa at the termination of an extensive calcrete drainage system (Heath, Deutscher & Butt, 1984). The mineralised area is at the western edge of an extensive calcrete platform extending over an area of 50 km^2. The higher concentrations of uranium extend over an area of about 1500 by 50 m with concentrations exceeding 0.045% U and maximum values in excess of 0.2% U. Mineralisation is mostly in the top 1–5 m, with the maximum concentrations close to the water-table. The carnotite forms patches and coatings in clay. Lower concentrations of uranium are also in orange-brown sandy clay underlying the calcrete platform to the east. A major calcrete channel extending for over 50 km to the northeast contains minor concentrations of up to 0.025% U (mostly 30–70 ppm U) in the silicified lower horizons of the calcrete close to the water table.

Near the northeast margin of the Yilgarn Block, valley calcrete deposits extend over a distance of 33 km in the **Hinkler Well–Centipede** (Fig. 16) drainage system (Crabb, Dudley & Mann, 1984), which enters the southwestern side of Lake Way. In the western part of the system the valley calcrete is over 2 km wide, but it narrows to 0.5 km before broadening into a chemical delta on entering Lake Way. The thickness of the calcrete also decreases from 15 m to 5 m down-drainage. Carnotite mineralisation in the main valley calcrete is known as the Hinkler Well prospect, and the carnotite mineralisation in the chemical delta constitutes the Centipede uranium deposit. Isolated lenses of up to 0.01% U occur in the Hinkler Well area, and the main zone of 1 x 3 km is associated with carbonated weathered granite. In the chemical delta, uranium mineralisation forms three discrete pods. In the main pod the host rock is mainly a soft, grey to black, manganiferous calcrete, covered by less than 2 m of overburden. In the other pods uranium occurs in hard and soft calcrete overlain by up to 6 m of overburden. The thickess of the mineralised zones varies from 1–5 m, with grades of up to 0.2% U.

At the **Dawson Well** prospect, 8 km west of Hinkler Well, uranium mineralisation occurs in calcrete.

The joint-venture partners in the Yeelirrie project drilled several small calcrete uranium deposits in the Yilgarn Block. These include **Ankatel,** 160 km south of Yeelirrie; **Nowthanna,** 140 km west of Yeelirrie; **Windimurra,** 200 km southwest of Yeelirrie; **Cogla Downs,** 125 km west of Yeelirrie; **Murchison Downs,** 115 km west-northwest of Yeelirrie; and **Wondinong,** 180 km west-northwest of Yeelirrie.

Calcrete deposits outside the Yilgarn Block

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

Calcrete-type uranium mineralisation has also been reported south of the Ngalia Basin, NT (Fig. 24) (Stewart, 1982). At several localities carnotite is known to occur in channel calcrete and calcareous sand in the Tertiary drainages that cross the Stuart Bluff Range. The low-grade **Napperby** deposit trends northeast, and is several kilometres long by 1500 m wide (Akin & Bianconi, 1984). The mineralised layer is 1 to 3 m thick and is at a shallow depth in calcareous clayey sand overlain by calcareous sediment. The uranium minerals are carnotite and minor amounts of tyuyamunite. Another calcrete-type uranium deposit, **Currinya,** 120 km west of the Napperby deposit, is near the southern edge of the Ngalia Basin. Carnotite occurs in Quaternary calcrete and sandy clay. The mineralisation is patchy and discontinuous and grades are low.

DISSEMINATED MAGMATIC, PEGMATITIC AND CONTACT DEPOSITS IN IGNEOUS AND METAMORPHIC ROCKS

Mary Kathleen–Mount Isa uranium field

There was a period of intensive exploration for uranium in the Early–Mid Proterozoic Mount Isa Block (Fig. 25) from 1954–1956. The first discovery — at Skal, 32 km north of Mount Isa — was made by a prospector in early 1954 (Brooks, 1975). Anderson's Lode and the Valhalla deposit were also discovered by prospectors in 1954 and in July of that year prospectors discovered Mary Kathleen. In 1954, Mount Isa Mines Ltd (MIM) completed an airborne scintillometer survey over the Eastern Creek Volcanics and other basic volcanics. Rio Tinto Australian Exploration Pty Ltd carried out airborne surveys over the Corella Formation (Searl & McCarthy, 1958) and BMR similarly surveyed the contact zones of granite intrusions (Parkinson, 1956). There have been no significant discoveries in the region since 1954.

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

There was a third period of active exploration from 1979–1982. MKU mounted another major program in an effort to locate and/or delineate further ore for treatment at Mary Kathleen, anticipating the exhaustion of economic reserves at the Mary Kathleen deposit. Deposits drilled included Elaine, Rita, Rary, Turpentine, Flat Tyre, and Emancipation. In 1974, Agip bought several deposits in the Eastern Creek Volcanics from QML and tested many of them from 1974–1981. Several companies carried out regional radiometric surveys and then tested the anomalies detected. Exploration was also carried out in Tertiary sands near the margins of the Mount Isa Block.

The Mary Kathleen deposit was the only deposit in the Mount Isa Block to be developed for production. The development of many deposits was inhibited by the refractory nature of the mineralisation (Brooks, 1975).

Regional geological setting

The regional geology and stratigraphy of the Mount Isa Block have been described by Carter, Brooks, & Walker (1961); Plumb & Derrick (1975); Derrick, Wilson, Hill, Glikson, & Mitchell (1977); Derrick (1980); Plumb, Derrick, & Wilson (1980); and in various 1:100 000 geological map commentaries. An updated synthesis is to be published shortly by BMR (Blake, in press).

The Proterozoic terrane comprises three major palaeogeographic units. A north-trending central belt of granitic and volcanic basement, the Kalkadoon–Leichhardt Block, is flanked on the east by the Mary Kathleen Shelf and on the west by the Leichhardt River Fault Trough. The Mary Kathleen Shelf comprises several thin sequences of shallow-water shelf sediments (Plumb & others, 1980) that have undergone complex folding, regional metamorphism, and granitic intrusion and metasomatism. The Leichhardt River Fault Trough is a palaeotectonic trough containing thick sequences of basalt and shallow-water sedimentary rocks now folded, faulted, and regionally metamorphosed.

In the Mary Kathleen Shelf sequence there are several uranium deposits in metamorphics of the Middle Proterozoic Corella Formation. Mary Kathleen is the largest and there are about 40 minor prospects, mainly up to 20 km to the northeast and south of it (Brooks, 1975). There are also some minor deposits east and south of Cloncurry, in the Soldier's Cap Formation, Marimo Slate, and Kuridala Formation.

At Mary Kathleen, basement rocks crop out to the west of the mine area. These are metamorphosed felsic volcanics and sediments of the Argylla Formation, the uppermost unit of the Tewinga Group (Plumb & others, 1980). The orebody is in the Corella Formation and occurs on the western limb of the north-plunging Mary Kathleen Syncline (Scott & Scott, 1985).

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

The youngest rocks of the Argylla Formation have been dated at 1780 Ma. The Burstall Granite and rhyolite dykes intruded the Corella Formation at about 1740 Ma. Hence the Corella Formation was deposited in the period between 1780 and 1740 Ma (Page, 1983).

In the Leichhardt River Fault Trough, uranium deposits are confined mainly to the Eastern Creek Volcanics (metabasalt with interbedded quartzite, metagreywacke, conglomerate, slate, and tuff; Carter & others (1961); Derrick & others (1977)). Brooks (1975) reported that, of the 107 uranium prospects recorded, 41 warranted drilling, in four main areas — Spear Creek, Gorge Creek, Paroo Creek, and Calton Hills. The largest and best known are Valhalla, Skal, and Anderson's Lode.

Mary Kathleen deposit

The geology (Fig. 26) has been described in detail by Hughes & Munro (1965), Hawkins (1975), Derrick (1977), and Scott & Scott (1985). The main rock types are cobble conglomerate, 'igneous-textured granofels', diorite, calc-silicate granofels, quartzite, amphibolite, and impure marble. Cobbles in the conglomerate are well-rounded and consist of either microcline, quartzite, diopside, or garnet, and the matrix consists of feldspar, diopside, and minor garnet.

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

The orebody is surrounded by an extensive irregular alteration zone consisting mainly of garnet (andradite-grossularite) with lesser amounts of diopside, scapolite, and feldspar. Where alteration is incomplete, garnet and diopside form veins and lit-par-lit injections. In the centre of the orebody alteration is virtually complete and only small remnants of altered diorite and cobble conglomerate remain (Mary Kathleen Company Geologists, 1981). Altered diorite in the open cut is stratigraphically equivalent to a diorite unit outcropping along strike from the mine area.

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

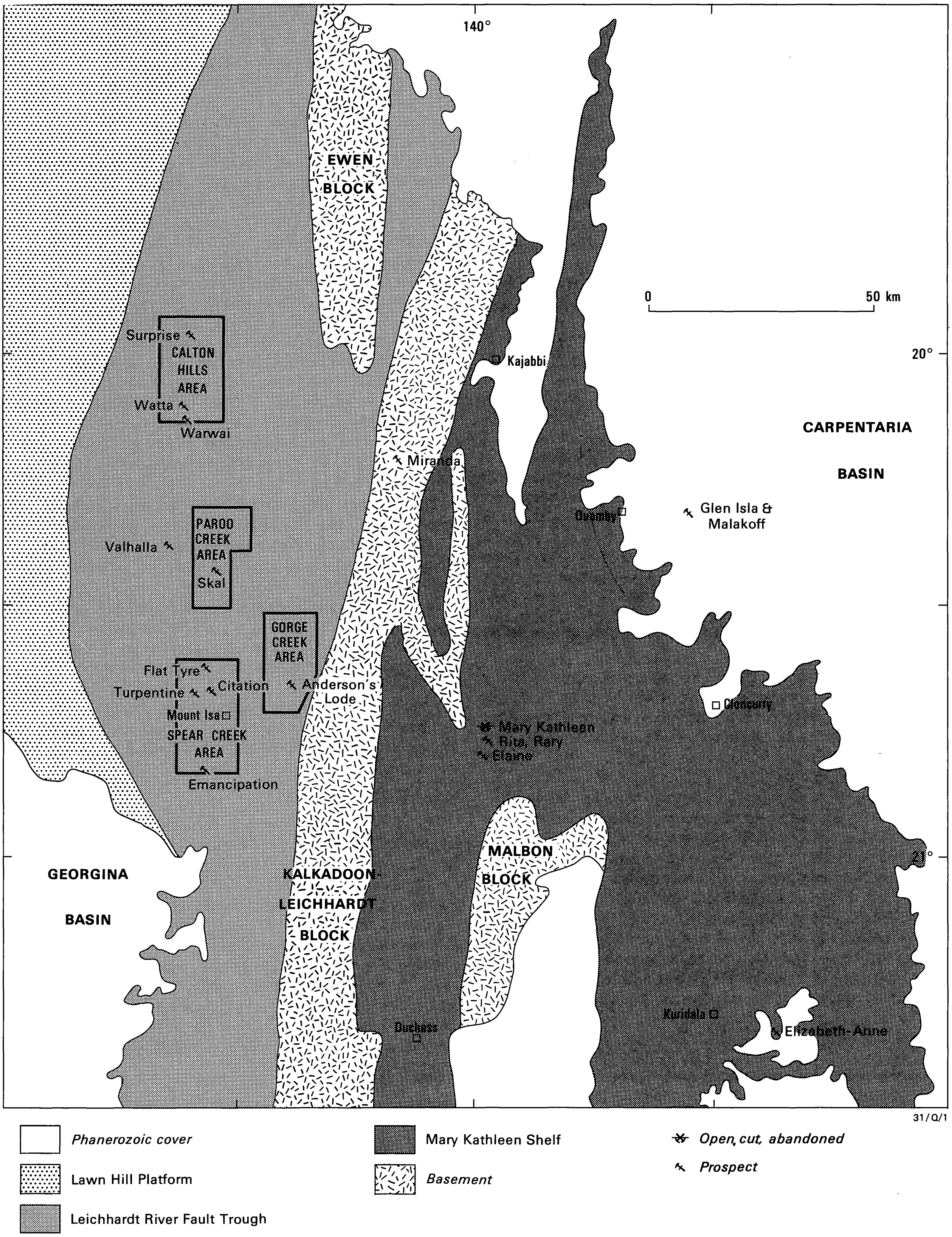


Fig. 25. Principal uranium prospects in the Mount Isa–Mary Kathleen area.

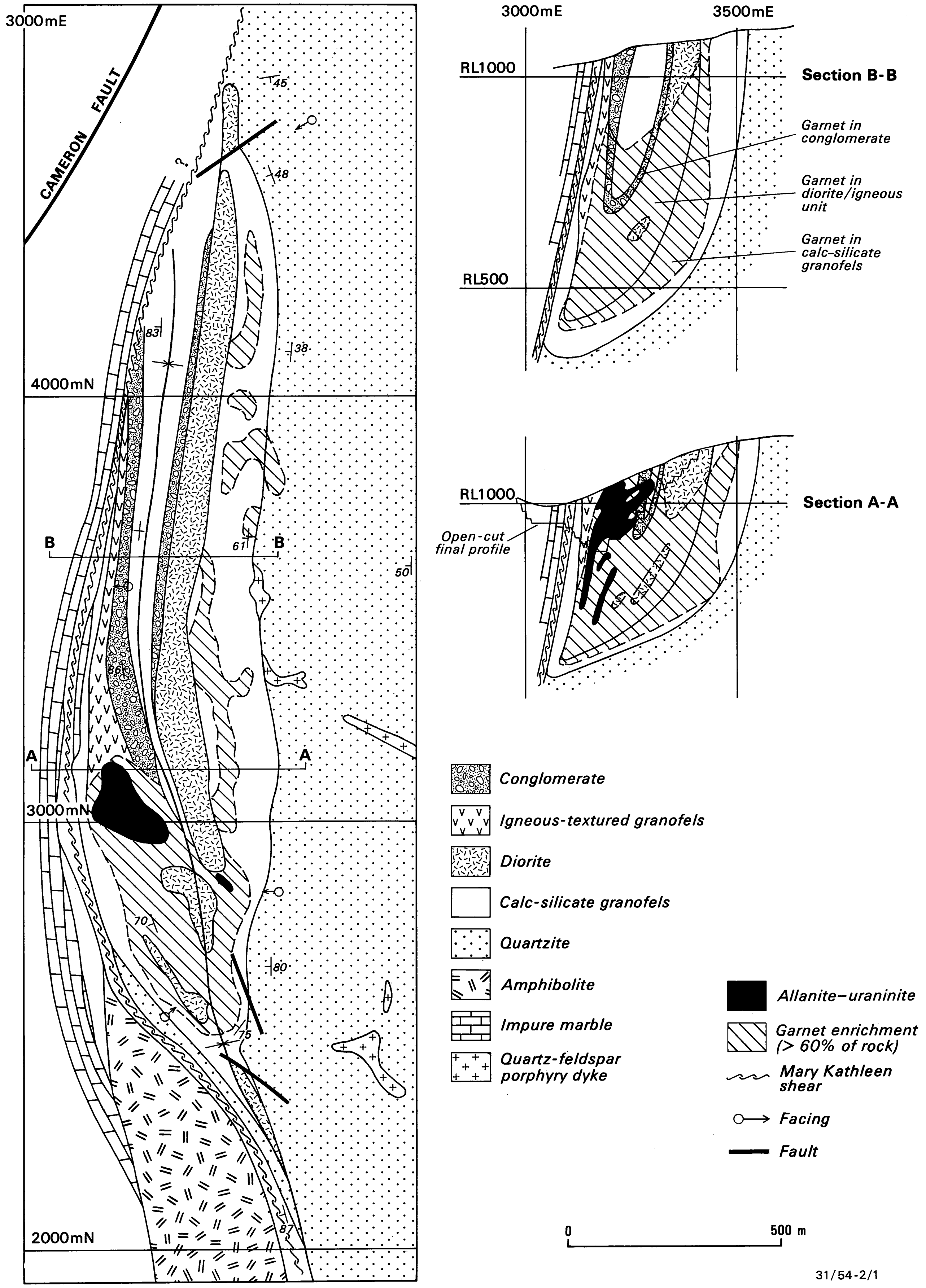


Fig. 26. Geology of the Mary Kathleen deposit (after Scott & Scott, 1984).

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

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

The origin of the orebody is conjectural and several theories have been proposed. Hawkins (1975) suggested that uranium was derived from the sedimentary pile and remobilised to its present site during metamorphism. A pyrometasomatic origin for the mineralisation was suggested by many authors including Matheson & Searl (1956), Derrick (1977, 1980), and Cruikshank, Ferguson, & Derrick (1980). These authors proposed that metasomatic alteration and mineralisation were related to the release of residual hydrous phases from the Burstall Granite or associated felsic dykes (dated by Page (1983) at about 1740 Ma). However, the uraninite gives an age of 1550 ± 15 Ma, and the skarn formation an age of 1200 Ma. Thus there cannot be a simple genetic link between magmatism, skarn formation, and uranium mineralisation (Page, 1983). Scott & Scott (1985) suggested that the alteration and mineralisation are genetically related to basaltic volcanism and associated hydrothermal activity during deposition of the Corella sediments. Field evidence indicates that both the diorite and the igneous-textured granofels were originally volcanic flows.

The orebody was discovered in July 1954 and production of uranium oxide from the treatment plant began in June 1958. The total resources within the orebody before mining started were estimated as 9 483 000 t of ore averaging 0.131% U_3O_8 (Hawkins, 1975), i.e. an initial resource of 12 000 t U_3O_8.

From 1958 to 1963, 4080 t of U_3O_8 was produced to fulfil a contract with the United Kingdom Atomic Energy Authority. The operation was then placed on care-and-maintenance as no further contracts could be obtained.

A revival in world demand for uranium in the late 1960s enabled the company to secure new sales contracts. Production of U_3O_8 resumed in 1976 and from then until the end of operations in October 1982, a further 4802 t U_3O_8 was produced (Mary Kathleen Uranium Ltd, 1983).

After mining ended, the resources below the open cut were estimated to amount to 1200 t of U_3O_8 (Mary Kathleen Uranium Ltd, 1981). The company reported that this could not be extracted at a profit because of the high mining costs involved and the low prices for spot-market sales at that time.

Other deposits in the Mary Kathleen Shelf sequence

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

At the **Elizabeth-Anne** prospect, 10 km east-southeast of Kuridala, uraninite-brannerite mineralisation fills fractures in a banded-iron-formation where this unit has been intruded by a dolerite dyke (Donchak, Blake, Noon, & Jacques, 1983; Hoskins & Scott, 1983), and davidite and brannerite occur in pegmatite and granite intruding the Corella Formation (Brooks, 1975).

Deposits in the Leichhardt River Fault Trough sequence

Most of the 107 occurrences recorded are in the Eastern Creek Volcanics; a few minor prospects are in the underlying Leander Quartzite. Brooks (1960, 1972, 1975) has described the geology and mineralogy of these stratabound prospects, which typically form steeply dipping tabular to pipe-like bodies.

There are five principal host rock types: (1) tuff (Valhalla, Watta, and Warwai); (2) siltstone (Skal); (3) greywacke (Anderson's Lode); (4) hornblende-allanite schist (many small deposits in the Spear Creek area — the schist is probably metamorphosed basic volcanics); and (5) basalt (Surprise). Basic volcanics are associated with virtually all deposits in the Eastern Creek Volcanics; sedimentary host rocks are interbedded with the volcanics. The primary uranium mineral is fine-grained disseminated brannerite, commonly associated with magnetite/hematite, and in places with sphene, biotite, rutile, ilmenite, and zircon. Secondary calcite and dolomite are present in the gangue (relevant when considering a leaching process for processing these ores) (Brooks, 1975). Minor pyrite and chalcopyrite have been recorded. The secondary uranium minerals are metatorbernite, uranophane, and carnotite.

The largest known deposit in the Eastern Creek Volcanics is **Valhalla,** 45 km north-northwest of Mount Isa. In 1968 Queensland Mines Ltd was granted leases over the deposit and carried out an extensive drilling program from 1968–1970 (Queensland Mines Ltd, 1970). The mineralisation occupies a steeply-dipping ferruginous tuff horizon interbedded with metabasalt and shale (Brooks, 1975). In the weathered zone metatorbernite is the main mineral; in the primary zone, uranium occurs in brannerite and a zircon-type mineral (Henley, Cooper, & Kelly 1972). Mineralisation extends over a length of 730 m and a width of more than 15 m. Queensland Mines Ltd (1973) reported that the resources, using a cut-off grade of 0.1% U_3O_8, were:

probable — 3810 t contained U_3O_8, average grade 0.19%
possible — 1663 t contained U_3O_8, average grade 0.20%

The **Skal** deposit, 35 km north of Mount Isa, was tested in 1954 by Mount Isa Mines Ltd. Queensland Mines Ltd bought the leases in 1959, and drilling was carried out in 1959–60 and again in 1968–69. Finely disseminated brannerite (in association with magnetite/hematite, calcite, and minor chalcopyrite and pyrite) occurs in a brecciated siltstone interbedded with basic volcanics (Brooks, 1975). The southern zone measures 152 m by 18 m and the northern zone 120 m by 23 m. Queensland Mines Ltd (1973) reported that possible resources, at a cut-off grade of 0.05% U_3O_8, total 3447 t of contained U_3O_8, averaging 0.13%.

Anderson's Lode (Counter deposit), 14 km northeast of Mount Isa, is in a lens of altered greywacke interbedded with altered basalt. Dolerite dykes occupy transverse faults and form the eastern and western limits of the mineralisation. In outcrop the deposit is 46 m long and 17 m wide (Brooks, 1960). Gangue minerals include hematite, ilmenite, calcite, sphene, and rutile. Queensland Mines Ltd (1973) reported that probable resources, at a cut-off grade of 0.1% U_3O_8, total 1179 t of contained U_3O_8, averaging 0.20%.

The many small deposits in the Spear Creek area are hosted by amphibolite and hornblende-allanite schist (metamorphosed basalt; Brooks, 1975). The primary mineral is uraninite. These prospects were tested by MIM and subsequently by QML prior to 1971. From 1979–80, Urangesellschaft Australia Pty Ltd drilled **Turpentine** and **Folderol** (5 km northeast of Turpentine) (Gooday & McKinnon-Love, 1980). In 1980, Kelvin Energy drilled the **Ardmore East** prospect, 90 km south of Mount Isa (Chan, 1981). In 1980–81, MKU explored and drilled the Turpentine, **Flat Tyre, Citation,** and **Emancipation** prospects.

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

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

Olary and Mount Painter fields

Until 1944 the only two significant occurrences of uranium mineralisation known in Australia were at Radium Hill and Mount Painter, SA (Fig. 20). Radium Hill, in the Olary field, 340 km northeast of Adelaide, was discovered in 1906. In 1910 uranium-bearing minerals were also found at Radium Ridge in the Mount Painter field, 260 km to the northwest.

Radium was mined intermittently from the Mount Painter field and Radium Hill until 1934, when both were forced to close down owing to the complex mineralogy of the ores and the discovery of pitchblende at Great Bear Lake in Canada (Campana & King, 1958; Australian Atomic Energy Commission, 1962).

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

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

Both the Olary and Mount Painter fields were extensively explored for uranium from 1968–1982.

Regional geological setting

Radium Hill, Crocker Well, and Mount Victoria are in the western part of the Early to Middle Proterozoic Willyama Complex (known as the Olary Province in South Australia). The complex consists of metasediments and gneiss which underwent three phases of deformation and metamorphism in the Proterozoic. Late-tectonic granitoids and associated pegmatite were intruded during the last phase. Thorian brannerite, as at Crocker Well, is consistently associated with sodic granite, and many of the pegmatites contain uranium, thorium, and rare-earth-element minerals. At Mount Victoria, granite and migmatite contain pods of biotite-scapolite-quartz schist containing abundant rutile, davidite, zircon, monazite, and xenotime. At Radium Hill, davidite ore occurs as replacements along shears and fractures in paragneiss and amphibolite of the Willyama Complex (Whittle, 1954; Blisset, 1975; Ashley, 1984; Ludwig & Cooper, 1984).

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

Wilson, Compston, Jeffrey, & Riley (1960) estimated the age of davidite from Crocker Well at 1600 Ma. Cooper (1972) reinterpreted early U-Pb age determinations on thorian brannerite from Crocker Well and indicated a preferred age of 1705 Ma for the primary crystallisation and identified episodic Pb loss at 513 Ma. Further work by Ludwig & Cooper (1984) on U-Pb-Th data from Crocker Well, Mount Victoria, and Radium Hill yielded very scattered and discordant apparent ages, but the results obtained are consistent with primary ages of about 1580 Ma for Crocker Well and even older for Radium Hill and Mount Victoria.

About 260 km north-northwest of the Olary field is the Mount Painter Block of Early to Middle Proterozoic metasediments and metavolcanics (Radium Creek Metamorphics) and Middle Proterozoic granite, pegmatite, and amphibolite dykes. These rocks are collectively known as the Mount Painter Complex which is intruded by early Palaeozoic granite. The uranium mineralisation is in granitic and hematitic breccia which form irregular bodies in metasediments and older granite of the basement complex.

Lambert, Drexel, Donnelly, & Knutson (1982) have suggested that the main cause of brecciation was the ascent of Delamerian (Ordovician) granitic magmas to high levels within a major zone of faulting. The rapid release of late-stage vapours caused hydraulic fracturing and K-metasomatism. Ensuing hydrothermal activity introduced Fe, Si, and U into hematitic breccias.

The Mount Painter deposits are now included with the disseminated magmatic, pegmatitic and contact deposits because of the close genetic association with the Ordovician granite. Youles (1978, 1986) and Major (1978), on the other hand, consider that sedimentary processes were important in the formation of the breccias. They also believe that, in broad lithological terms, the geological setting of the Mount Painter deposits is similar to that at Olympic Dam.

Blisset *in* Coats & Blisset, (1971) considers that the secondary uranium mineralisation in the Mount Painter area was formed by the action of circulating groundwater during Tertiary peneplanation and deep weathering.

Olary field

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

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

The host rocks are paragneiss and amphibolite of the Willyama Complex, folded into a dome-like structure. The orebodies occupy northeast-striking, steeply dipping, subparallel shear zones cutting dragfolds on the overturned western limb of the dome. The main ore mineral was davidite, intergrown with iron and titanium oxides, and the main gangue was biotite and quartz. Small amounts of pyrite, chalcopyrite, and arsenopyrite were present in all lodes. Within 30 m of the surface, carnotite was the main secondary uranium mineral. Whittle (1954) concluded that the davidite was formed by partial replacement of existing intergrowths of hematite, ilmenite, and rutile by uranium and rare-earths introduced by aplite dykes.

The **Mount Victoria** deposit (Campana & King, 1958) is 90 km west-northwest of Radium Hill and was discovered in 1954. It has been tested by drilling and underground exploration. Uranium mineralisation is localised along a system of south-dipping fracture zones in foliated migmatitic granite and gneiss. The mineralisation consists of 'disseminated daviditic iron-titanium minerals in a matrix of medium-grained biotite, albitic feldspar, and apatite'. Impure davidite, rutile, and hematite occur as composite granules and irregular segregations replacing or partly replacing the biotitic matrix. The ore is regarded as metasomatic, from a granitic source. King, *in* Campana & King, (1958), estimated the probable reserves as 69 000 t of ore at 0.31% U_3O_8 and a possible resource as 41 000 t of ore at 0.22% U_3O_8. More recently North Flinders Mines Ltd (1979) stated that mineable reserves were conservatively estimated at 66 000 t of ore with production grades of about 0.3% U_3O_8.

The **Crocker Well** deposits (Dickinson, Wade, & Webb, 1954; Campana & King, 1958; Ashley, 1984), about 10 km south of Mount Victoria, were detected by an airborne reconnaissance survey in 1951. Ashley (1984) stated that a resource of at least 10 000 000 t of mineralisation averaging 500 ppm U_3O_8 to a depth of 100 m has been outlined. Thorian brannerite mineralisation at the Crocker Well prospect occurs in sodic granite, trondhjemite, and sodic alaskite, and associated sodic felsic gneiss. There are several zones of mainly fracture-controlled and disseminated mineralisation in an area of about 4 km². Significant uranium-thorium mineralisation is restricted to fractures and local phlogopite-rich breccias. The breccias form diatreme-like bodies and dykes, ranging from less than 1 cm to 40 m across, which contain angular inclusions of adjacent granitic rock and gneiss in a phlogopite-rich matrix. The higher-grade uranium-thorium mineralisation is accompanied by higher fluorine values (Ashley, 1984).

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

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

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

Mount Painter field

Most of the uranium prospects and deposits occur within an area of 30 km² near Mount Painter. Host rocks to the uranium deposits are granitic and hematitic breccias which occur as irregular bodies within metasediments and older granites of the basement complex. Most of the clasts in the granitic and hematitic breccias are of the nearest country rock type; granitic breccias are the most common type. Locally, hematite and/or chlorite form more than 50% of the rock volume. The highest uranium content occurs in hematitic and chloritic breccias.

The uraninite occurs in a chlorite-hematite gangue and is typically very fine-grained. The main secondary uranium mineral in the weathered zone is torbernite — others include autunite, metatorbernite, uranophane, and gummite; chlorite has been altered to hematite and goethite. The chief gangue minerals are hematite, fluorite, barite, and manganese oxides.

The main deposits in the hematitic breccias are **Mount Gee, Armchair, Streitberg,** and **Radium Ridge.** Youles (1975) states that in general, the uranium and sulphide content increases as the primary hematite-to-chlorite ratio increases.

The **Hodgkinson** deposit (Youles, 1975) occurs in foliated, brecciated, and rebrecciated granitic rock. Chlorite and hematite are absent.

North Flinders Mines Ltd (1981 Annual Report) stated that continuing exploration at the **Gunsight** prospect, 40 km northeast of Mount Painter, had established that uranium is associated with copper, cobalt, and rare earths. 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 Late Proterozoic sedimentary rocks next to the Mount Painter Complex.

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

Hodkingson — 226 800 t ore at 0.25% U_3O_8
Radium Ridge — 3 628 800 t ore at 0.06% U_3O_8
Mount Gee — 2 721 600 t ore at 0.1% U_3O_8
Armchair-Streitberg — 1 814 400 t ore at 0.1% U_3O_8

Gascoyne Block

In the Gascoyne Block, WA (Fig. 16), uraninite-bearing pegmatites occur in the Early Proterozoic Morrissey Metamorphic Suite, which is widely migmatised. Intrusive pegmatite and alaskite form extensive belts throughout the Morrisey Metamorphics and the alaskite closely resembles the host rocks at the Rossing uranium deposit in Namibia (Carter, 1982).

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

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

Strangways Range, central Australia

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

VEIN DEPOSITS

Georgetown–Townsville uranium field

The BMR carried out regional airborne scintillograph and ground geological reconnaissance surveys over the Georgetown Inlier in the 1950s. No significant uranium discoveries resulted (Bain, 1977).

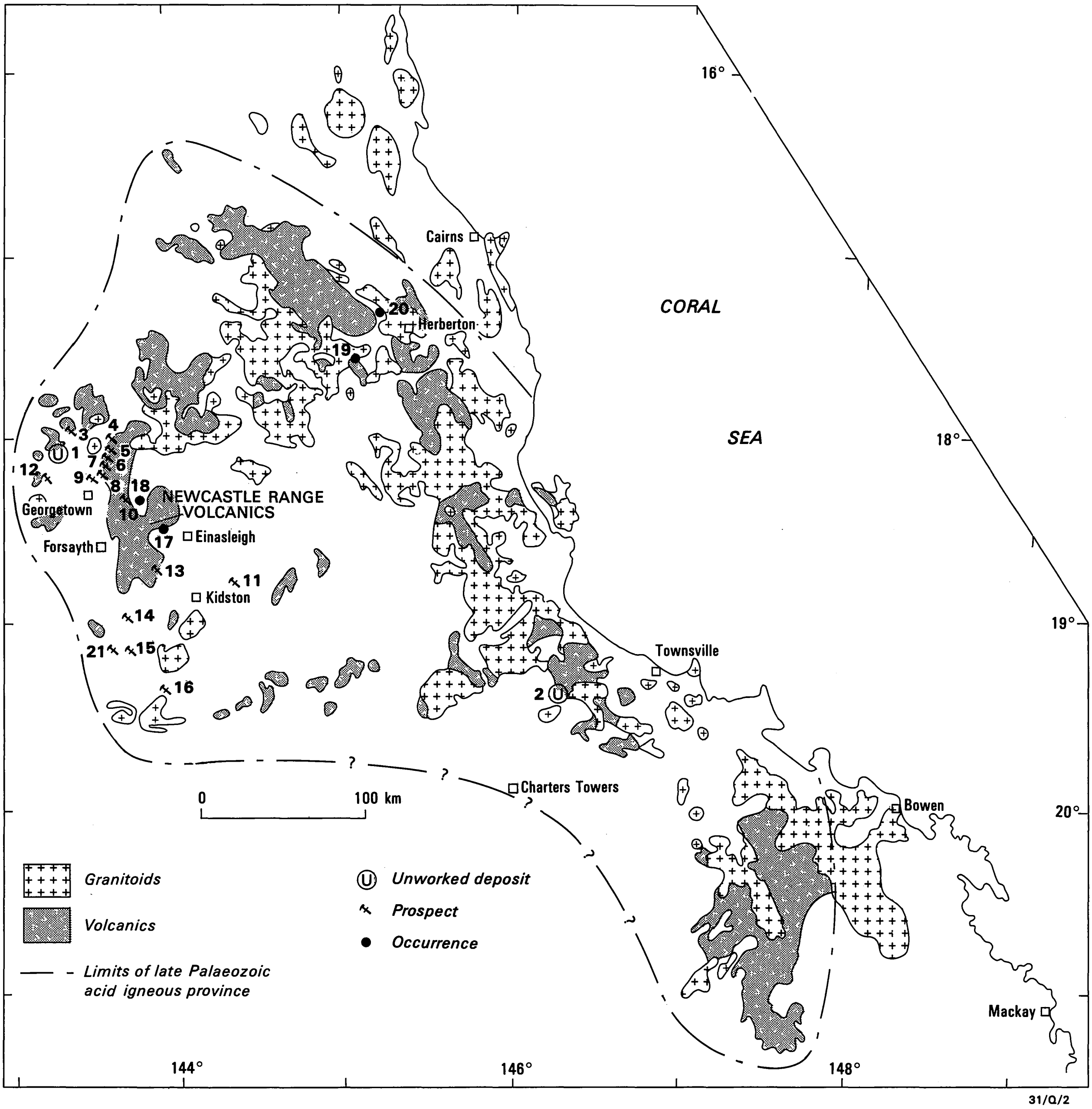
Central Coast Exploration NL began work in the Georgetown area (Fig. 27) in 1969 (O'Rourke, 1975). Initially the work was directed at assessing the base-metal potential, but as exploration progressed, the company decided to include uranium. Airborne radiometric and magnetic surveys carried out in July 1971 led to the discovery of outcrops of the Maureen deposit. The first holes were drilled in 1972. The discovery led to a rapid increase in uranium exploration throughout the Georgetown Inlier from 1972–1979. This work spread progressively southwards, covering areas of Carboniferous acid volcanics as far south as Townsville. Details regarding the companies involved and the areas covered are listed by Withnall (1976). In 1971, Pioneer Mining & Exploration Pty Ltd drilled the Laura-Jean prospect, in the Newcastle Range Volcanics.

Devonian–Carboniferous sedimentary sequences in the Gilberton, Bundock, Clarke River, Burdekin, and Drummond Basins were extensively explored for sandstone uranium deposits (Noon, 1979), but no significant discoveries were reported.

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

Regional geological setting

Proterozoic metamorphics and granite of the Georgetown Inlier occupy much of the western part of the Cairns–Townsville hinterland. Palaeozoic sedimentary rocks and local metamorphics of the Hodgkinson Basin and Broken River Embayment occur in the east. Late Palaeozoic acid volcanics and associated granite occur throughout the region (Fig. 27).



31/Q/2

Fig. 27. Granitoids, volcanics, and uranium deposits, prospects, and occurrences in the late Palaeozoic acid igneous province, Georgetown–Townsville uranium field: 1 Maureen, 2 Ben Lomond, 3 Turtle Arm, 4 Dagworth, 5 Fiery, 6 Galah, 7 Twogee, 8 Trident, 9 Phillips Well, 10 Laura Jean, 11 Oasis, 12 Lineament Group, 13 Chinaman Creek, 14 Limkins, 15 Mount Hogan, 16 Werrington Group, 17 Kaiser Bill, 18 Quest End, 19 Treasure, 20 Stannary Hills, 21 Gilberton Basin (after Bain, 1977; and Bain & Whitnall, 1984).

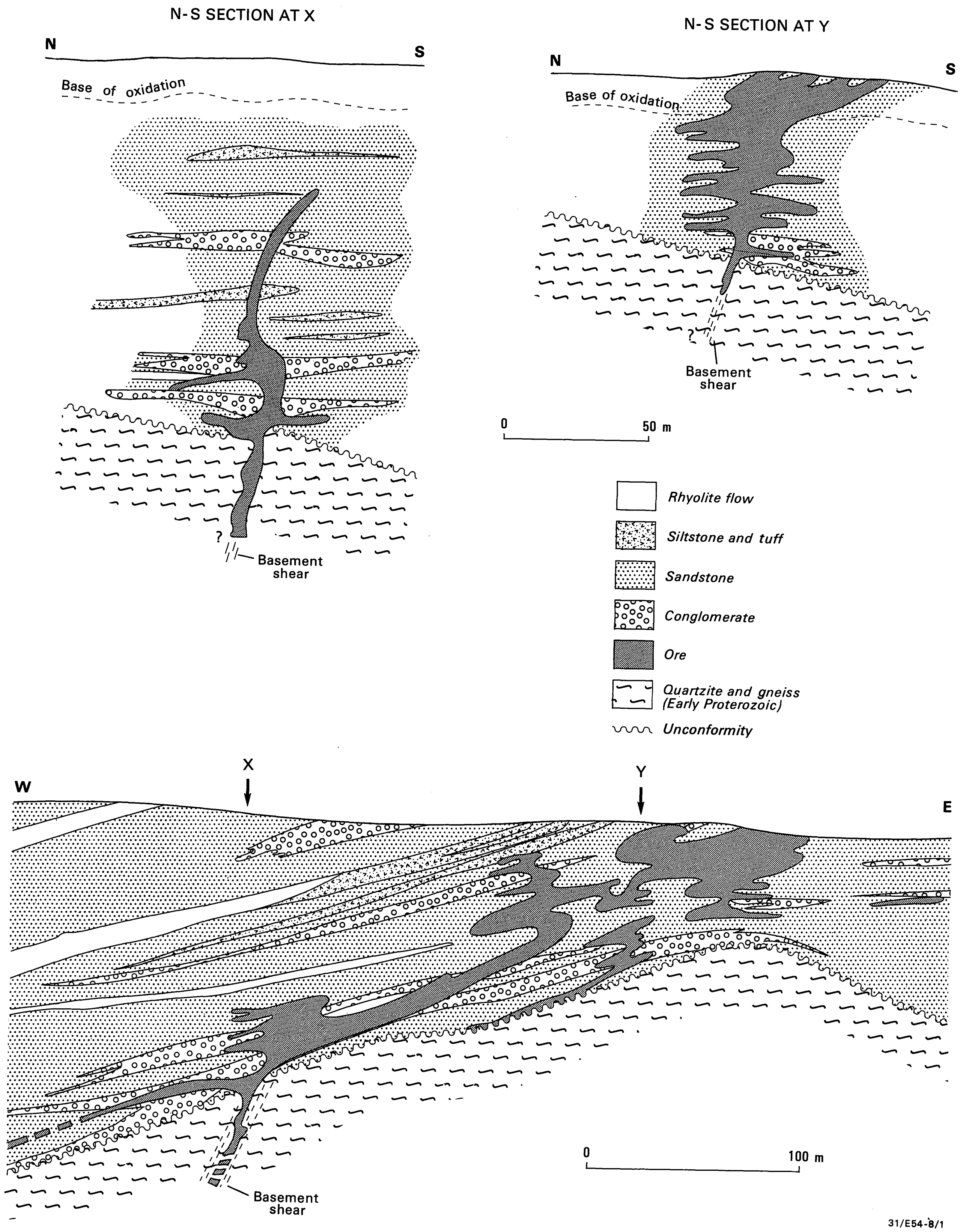


Fig. 28. Long-section and cross-sections of the Maureen deposit (after Bain & Withnall, 1980).

The regional geology has been described by Bain & others (1983), Levingston (1981), Henderson (1980), Withnall, Bain & Rubenach (1980), Blake (1982), Wyatt, Paine, Clarke, & Harding (1970), de Keyser & Lucas (1968), and White (1965). The basement rocks of the Inlier are Early and Middle Proterozoic metasediments and metavolcanics — mainly mica schist, biotite gneiss, quartzite, pegmatite, and fine-grained granulite (phyllite, slate, and ignimbrite occur in the low-grade metamorphic areas). The metamorphics have been intruded by Middle Proterozoic S-type and Siluro–Devonian I-type batholiths with development of migmatite.

The late Palaeozoic acid volcanic province (Fig. 27), to which the uranium deposits are believed to be related, extends over a large area and comprises many comagmatic calc-alkaline volcanic complexes, ring dykes, granitoids, and areas of related hydrothermal alteration. The province has been mapped and described by Branch (1966) and by Oversby, Black, & Sheraton (1980). The volcanic complexes and related intrusions are preserved in fault-bounded cauldron-subsidence areas, e.g. Newcastle Range Volcanics. Dyke swarms, breccia pipes, and hydrothermal alteration systems are commonly associated with cauldron subsidence.

The volcanics are dominantly grey to pink rhyolitic ignimbrite with intercalated tuff, breccia, agglomerate, and volcanoclastic beds. Some sequences are underlain by coarse, feldspathic, terrestrial clastics.

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

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

Maureen deposit

The Maureen deposit is 35 km northwest of Georgetown (Figs. 27, 28). Uranium-fluorine-molybdenum mineralisation forms irregular stratabound zones in a late Palaeozoic sequence (Maureen Volcanics) of conglomerate, sandstone, and siltstone, and overlying volcanics. The Maureen Volcanics are predominantly rhyolitic ignimbrite and agglomerate with subordinate basalt and clastic strata. The clastics are markedly thicker (320–400 m) in the vicinity of the deposit, which is in the lowermost 60 m. The sequence directly overlies Etheridge Group metamorphics on the northwestern edge of the Georgetown Inlier (O'Rourke, 1975).

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

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

The estimated in-situ resources for the Maureen deposit (Central Coast Exploration NL, 1979) are shown in Table 12. Possible resources have not been calculated. A cut-off grade of 0.035% U_3O_8 was used for the calculations. Molybdenum resources were not reported.

Table 12. Estimated in-situ resources, Maureen deposit

	Ore(t)	*Grade (% U_3O_8)*	*$U_3O_8(t)$*
Proved	1 650 330	0.153	2528
Probable	732 670	0.056	412
Total	2 383 000	0.123	2940

Ben Lomond deposit

The Ben Lomond deposit, 60 km west-southwest of Townsville (Figs. 27 and 29), is in rhyolitic tuff of the Carboniferous St James Volcanics (Valsardieu & others, 1980).

Fig. 29. Cross-section, Ben Lomond deposit (after Minatome Australia Pty Ltd, 1983).

Basement rocks are the Precambrian Argentine Metamorphics, comprising schist, amphibolite, quartzite, and granitic masses (Wyatt, Paine, Harding, & Clarke, 1970). Continental redbeds of the Game Hill beds (Late Devonian–Early Carboniferous), unconformably overlie the basement, and are in turn overlain by the St James Volcanics. The St James Volcanics consist of a major lower unit of rhyolitic tuff with subordinate andesitic volcanics and clastics and an unconformably overlying unit ('Cattle Creek unit') of acid pyroclastics, tuffaceous clastics, and ignimbrite.

From the regional structure and distribution of faulting it appears that the lower unit accumulated in a cauldron-collapse structure (Valsardieu & others, 1980) and was deformed during cauldron subsidence. The uranium-molybdenum mineralisation is in a complex system of subparallel, steeply-dipping veins and fractures (Fig. 29) associated with a wide shear zone. The upper limit of the mineralised vein system is a few metres below the unconformity at the base of the Cattle Creek unit. Mineralisation is best developed 10–50 m below the unconformity. The vein system is mineralised over a length of more than 500 m, a maximum width of 150 m, and vertical depth of 100 m.

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

Mineable reserves in both the proposed open-cut and underground mine were estimated (Minatome Australia Pty Ltd, 1983) as 1 930 000 t ore averaging 0.209% U and 0.159% Mo. This represents 4035 t of contained U and 3026 t of contained Mo. Minatome proposed to mine the western part of the deposit by open cut, whereas an underground mine was proposed for the eastern part which is covered by a high ridge of the barren Cattle Creek unit.

Other deposits

The **Turtle Arm** prospect is located 5 km northeast of Maureen, and the mineralisation and host rocks are similar to Maureen.

There are several prospects along the western edge of the Newcastle Range Volcanics (Fig. 27), either within the basal epiclastics/volcanoclastics or in Proterozoic metasediments adjacent to the contact with the volcanics. In the metasediments, the mineralisation is closely associated with Carboniferous porphyritic acid, intermediate, and basic dykes (Crane, 1983). From 1972–1983, Minatome Australia Pty Ltd explored this area intensively by means of helicopter and fixed-wing airborne surveys, geological mapping, ground geophysics, and drilling. Many anomalies were tested and of these the main areas of mineralisation were at the Dagworth, Fiery, Galah, Twogee, Trident, and Phillips Well prospects (Crane, 1983). Hematite alteration is commonly associated with the mineralisation.

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

The **Fiery, Galah,** and **Twogee** prospects are where basal quartzofeldspathic sandstone, arkose, conglomerate, and minor siltstone of the Newcastle Range Volcanics were intruded by rhyolitic dykes and microgranite bodies. The area has been extensively faulted. Mineralisation has accumulated in zones of fracturing and brecciation in a variety of host rocks, including Proterozoic metasediments, rhyolitic dykes, arkosic clastics, ignimbrite, and andesite. At Twogee, total resources outlined by drilling amount to 640 t of contained U, averaging 0.099% eU (Crane, 1983).

The **Trident** prospect is in the Proterozoic basement rocks, 1 km west of their contact with the Newcastle Range Volcanics. Mineralisation occurs along the brecciated footwall of a dolerite dyke. In-situ resources amount to 420 t of contained U averaging 0.19% eU (Crane, 1983).

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

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

The **Oasis** prospect (25 km east-northeast of Kidston) was discovered by Australian Anglo American Ltd in 1973 and was originally called the Lynd Prospect (Hoyle, 1974). Staff of Central Coast Exploration NL renamed it when they drilled it in 1978–1979 (Central Coast Exploration NL, 1979). The mineralisation is in a small roof pendant of quartz-biotite-chlorite schist in Precambrian porphyritic granite, and extends over a length of 200 m. The primary mineralogy is fine-grained uraninite within the biotite and chlorite foliae. The secondary uranium (phosphate) minerals include autunite, meta-autunite, torbernite, sabugalite, and bassetite.

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

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

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

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

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

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

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

Pine Creek Geosyncline

Small parcels of ore have been produced from three small mines in the geosyncline (Fig. 5), from 1954–56 (Table 13), outside the three main uranium fields containing unconformity-related deposits.

Table 13. Production of uranium ore from vein deposits in the Pine Creek Geosyncline

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

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 Early Proterozoic 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 southeast 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 Early Proterozoic South Alligator Group.

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

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 southwest and 7 km northwest 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 northwest, in the Driffield Granite.

In the Alligator Rivers uranium field there is a small vein-type deposit at **Tadpole,** about 22 km northwest of Nabarlek. Uraninite occurs in pegmatite in quartz-mica schist and quartzite of the Nimbuwah Complex.

In the Mount Lofty Ranges, SA, east and northeast of Adelaide, uranium mineralisation occurs in inliers of the Early Proterozoic Barossa Complex near **Houghton** and at **Myponga** (Dickinson & others, 1954; Parkin, 1957; Ingram, 1974).

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

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

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

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

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

In the Olary field, the **Radium Hill** deposit may also be regarded as vein-type.

Other occurrences

Small base-metal vein deposits containing some uranium at **Mundong Well** (Fig. 16) in the Gascoyne Block, WA, occur as small shoots formed on slight bends in faults cutting migmatite, gneiss, and schist of the Early Proterozoic Wyloo Group (Blockley, 1975). The principal uranium mineral is kasolite which is associated with cerussite, galena, sphalerite, malachite, chrysocolla, fluorite, calcite, and magnetite. The veins are close to a major regional unconformity, where the Wyloo Group is overlain by Middle Proterozoic sandstone of the Bangemall Basin. The discovery of this occurrence in the early 1970s led to a sudden increase in uranium exploration in the Gascoyne Block because the geological setting was considered similar to the Alligator Rivers uranium field.

Six small uranium prospects occur near Port Lincoln, SA (Fig. 17), in quartz-feldspar-hornblende gneiss and amphibolite of the Middle Proterozoic **Lincoln Complex** (Johns, 1961). Pitchblende forms disseminations, fracture coatings, and veins.

QUARTZ-PEBBLE CONGLOMERATE DEPOSITS

Hamersley Basin

Low-grade uraninite mineralisation in association with thucholite pellets has been intersected in Archaean quartz-pebble conglomerate in the Hardey Sandstone, the lowermost unit in the Hamersley Basin (Hickman, 1983; Carter, 1981; Carter & Gee, in prep.) (Fig. 16). The Hardey Sandstone unconformably overlies Archaean granite and metamorphics of the Pilbara Block. The equivalent unit in the west Pilbara is the Cliff Springs Formation and in the Balfour Downs district it is the Beatons Creek Conglomerate (Hickman, 1983). The Hardey Sandstone, at most places, is at the base of the Fortescue Group. Within this group, basaltic units which overlie the Hardey Sandstone have recorded age dates of 2780 Ma (Carter & Gee, in prep.). Hence the lower Fortescue Group is similar in age to the Witwatersrand Supergroup of South Africa; however, it is significantly older than the Canadian Huronian

Supergroup (Elliot Lake conglomerate-hosted uranium deposits). The heavy-mineral assemblage in the Hardey Sandstone includes pyrite, monazite, zircon, and anatase. Significant concentrations of uranium have been recorded at Bonnie Creek, Warralong Creek, and Croydon.

At **Bonnie Creek** (30 km southwest of Nullagine), Cominco Exploration Pty Ltd and Esso Australia Ltd reported conglomerate containing up to 360 ppm U in drillcore and 1223 ppm U in surface samples. The highest values are in conglomerate that contains pyrite as poorly rounded detrital grains and large irregular masses in the matrix. In the mineralised areas, the conglomerate contains mostly quartz pebbles, whereas the unmineralised parts contain a large proportion of rock fragments.

At **Warralong Creek,** 130 km southeast of Port Hedland, a 1–2-m-thick conglomerate in the Hardey Sandstone contains minor uranium mineralisation.

A uraniferous conglomerate 30 km south-southwest of **Croydon homestead** assayed 427 ppm U over 2.9 m. However, drilling has shown that the mineralisation is irregular (Hickman, 1983).

Halls Creek area

In 1954, uranium mineralisation was discovered 35 km northeast of Halls Creek by prospectors of United Uranium NL (Dow & Gemuts, 1969, Carter & Gee, in prep.).

Detrital concentrations of thorogummite occur in the basal quartz-pebble conglomerate and quartz sandstone of the Archaean(?)–Early Proterozoic Saunders Creek Formation. BMR drilled the conglomerate in 1959 (Mercer, 1961) but only very narrow intersections (0.1 m) of low-grade uranium mineralisation were recorded. X-ray diffraction indicated a thorium:uranium ratio of 3:1 to 2:1.

Kimberley Basin

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

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

OTHER TYPES OF DEPOSITS

This heading also includes deposits of unknown type.

CRA Ltd, in its Annual Report published in May 1986, stated that, in late 1985, uranium mineralisation had been discovered at the **Kintyre** prospect (in the Rudall area, WA; Fig. 16), and that the discovery was to be followed up by a major drilling program. At the time of going to press (February 1987) no details of the geology or grade of the intersections had been published.

Uranium occurs in Cambrian phosphorite near **Duchess,** southeast of Mount Isa in northwest Queensland. Generally the uranium content is less than 100 ppm U (Ingram, 1974). These deposits have been mined intermittently for their phosphate-content but no uranium has been recovered.

APPENDIX 1. LIST OF AUSTRALIAN URANIUM DEPOSITS AND OCCURRENCES

PROTEROZOIC UNCONFORMITY-RELATED DEPOSITS

Alligator Rivers uranium field (NT)

Ranger 1 (No. 1 Orebody, No. 3 Orebody, Anomalies 2, 4, and 9), Nabarlek, Jabiluka, Koongarra, Ranger 68, Ranger 4, Hades Flat, Caramal, Austatom, Beatrice, Gurrigarri, Garrunghar, Mordijmuk, Arrarra, 7J

Rum Jungle uranium field (NT)

Dyson's, White's, White's East, Rum Jungle Creek South, Mount Burton, Mount Fitch, Kylie, Southeast Kylie, Mount Fitch North, Dolerite Ridge, Rum Jungle Creek, Area 55, Waterhouse, Woodcutter's, Brodribb, Ella Creek

South Alligator Valley uranium field (NT)

El Sherana, El Sherana West, Rockhole 1, Rockhole 2, O'Dwyer's, Sterrits, Palette, Saddle Ridge, Coronation Hill, Scinto 5, Scinto 6, Koolpin Creek, Skull, Sleisbeck

Turee Creek area (WA)

Angelo River, 'Noranda'

Killi Killi Hills area (WA)

Halls Creek area (WA)

Tennant Creek area (NT)

Edna Beryl, Northern Star

PROTEROZOIC STRATIFORM AND STRATABOUND DEPOSITS

Stuart Shelf region (SA)

Olympic Dam, Acropolis

SANDSTONE DEPOSITS

Frome Embayment uranium field (SA)

Beverley, Honeymoon, East Kalkaroo, Yarramba, Gould's Dam, Paralana–Pepegoona

Westmoreland–Pandanus Creek uranium field (NT & Qld)

Mageera, Oogoodoo, Jack, Langi, Garee, Junnagunna, Outcamp, Sue

Ngalia Basin (NT)

Bigrlyi, Walbiri, Dingo's Rest, Sunberg, Coonega, Karin

Amadeus Basin (NT)

Angela, Pamela

Officer Basin (WA)

Mulga Rock

Carnarvon Basin (WA)

Manyingee

Canning Basin (WA)

Oobagooma

Eyre Peninsula region (SA)

Malbooma, Wynbring, Narlaby, Yaninee

Other prospects

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

SURFICIAL DEPOSITS

Yilgarn Block (WA)

Yeelirrie, Lake Way, Thatcher Soak, Lake Mason, Lake Raeside, Lake Maitland, Lake Austin, Hinkler Well, Centipede, Dawson Well, Ankatel, Nowthanna, Windimurra, Cogla Downs, Murchison Downs, Wondinong

Outside the Yilgarn Block

Jailor Bore (WA), Lamil Hills (WA), Minindi Creek (WA), Napperby (NT), Currinya (NT)

DISSEMINATED MAGMATIC, PEGMATITIC AND CONTACT DEPOSITS IN IGNEOUS AND METAMORPHIC ROCKS

Mary Kathleen–Mount Isa uranium field (Qld)

Mary Kathleen, Rita-Rary, Elaine, Elizabeth-Anne, Valhalla, Skal, Anderson's Lode, Turpentine, Folderol, Ardmore East, Flat Tyre, Emancipation, Watta, Warwai, Miranda, Surprise, Citation

Olary field (SA)

Radium Hill, Mount Victoria, Crocker Well, Crocker Well East, Spring Hill, Thackaringa

Mount Painter field (SA)

Mount Gee, Armchair, Streitberg, Radium Ridge, Hodgkinson, Gunsight, Shamrock

Gascoyne Block (WA)

Mortimer Hills

Strangways Range, central Australia (NT)

Mordor Igneous Complex

VEIN DEPOSITS

Georgetown–Townsville uranium field (Qld)

Maureen, Ben Lomond, Turtle Arm, Dagworth, Fiery, Galah, Twogee, Trident, Phillips Well, Laura Jean, Oasis, Lineament group, Chinaman Creek, Limkins, Mount Hogan, Werrington group, Kaiser Bill, Quest-End, Treasure, Stannary Hills

Pine Creek Geosyncline (NT)

Adelaide River, George Creek, Fleur de Lys, ABC, Edith River, Tennysons, Hore and O'Connors, Yenberrie, Fergusson River, Tadpole.

Westmoreland–Pandanus Creek uranium field (NT & Qld)

Pandanus Creek (Eva), Cobar 2, King's Ransom, Old Parr, El Hussen

Other occurrences

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

QUARTZ-PEBBLE CONGLOMERATE DEPOSITS

Hamersley Basin (WA)

Bonnie Creek, Warralong Creek, Croydon

Halls Creek area (WA)

Saunders Creek Formation

Kimberley Basin (WA)

King Leopold Sandstone

OTHER TYPES (including deposits of unknown type)

Kintyre (WA), Duchess (Qld)

APPENDIX 2. OWNERSHIP OF URANIUM MINES AND MAJOR PROSPECTS AS AT 1 JULY 1986

Northern Territory	
Ranger	Energy Resources of Australia Ltd (operating company) owned (August 1986) as follows: Peko-Wallsend Ltd (33.2%); EZ Industries Ltd (31.0%); Rheinbraun Australia Pty Ltd, UG Australia Developments Pty Ltd, Interuranium Australia Pty Ltd, OKG, Japan Australia Uranium Resources Development Co. Ltd (25% combined); others, mainly Australian companies (10.8%).
Nabarlek	Queensland Mines Ltd (operating company) owned: Pioneer Concrete Services Ltd (50%); Ampol Ltd (50%); Ampol Ltd is owned 79% by Pioneer Concrete Services Ltd.
Jabiluka	Pancontinental Mining Ltd (65%) Texaco Oil Development Co. (35%)
Koongarra	Denison Australia Pty Ltd
Ngalia Basin (Bigrlyi, Walbiri & others)	Agip Nucleare (Aust.) Pty Ltd (41.04%), Yuendumu Mining Co. NL (29.56%), Central Pacific Minerals NL (17.48%), Offshore Oil NL (8.35%), Southern Cross Exploration NL (2.38%), Gulf Resources Ltd (1.19%)
Angela	Uranerz Australia Pty Ltd (50%), MIM Holdings Ltd (50%)
South Australia	
Olympic Dam	Western Mining Corporation Ltd (51%), BP Australia Ltd & BP Petroleum Development Ltd (49%)
Beverley	Western Nuclear Australia Ltd (50%), Oilmin NL, Petromin NL, and Transoil NL (50%)
Honeymoon	MIM Holdings Ltd (65.7%), CSR Ltd (34.3%)
Western Australia	
Yeelirrie	Western Mining Corporation Ltd (90%), Urangesellschaft Australia Ltd (10%)
Lake Way	Western Alluvials Pty Ltd (53.5%), Vam Ltd (46.5%)
Manyingee	Total Mining Australia Pty Ltd (77%), Urangesellschaft Australia and Elf Aquitaine Triako Mines Ltd (23%)
Mulga Rock	PNC Exploration (Australia) Pty Ltd
Thatcher Soak	Cultus Pacific NL (70%), Southern Ventures NL (30%)
Queensland	
Westmoreland	Urangesellschaft Australia Pty Ltd (40.18%), Queensland Mines Ltd (48.40%), IOL Petroleum Ltd (11.42%)
Maureen	Central Coast Exploration NL (70% owned by Barrack Mines Ltd)
Ben Lomond	Total Mining Australia Pty Ltd

APPENDIX 3. COMPOSITIONS OF URANIUM AND RELATED MINERALS MENTIONED

Autunite	$Ca(UO_2)_2(PO_4)_2.10\text{–}12\,H_2O$
Bassetite	$Fe(UO_2)_2(PO_4)_2.8H_2O$
Beta-uranophane	$Ca(UO_2)_2\,Si_2O_7.6H_2O$
Brannerite	$(U,Ca,Ce)(Ti,Fe)_2O_6$
Carnotite	$K(UO_2)_2(VO_4)_2.3H_2O$
Coffinite	$U(SiO_4)_{1-x}(OH)_{4x}$
Curite	$Pb_2U_5O_{17}.4H_2O$
Davidite	$A_6B_{15}(0,OH)_{36}$, where A = Fe^{+2}, rare earths, U, Ca, Zr, and Th, and B = Ti, Fe^{+3}, V, and Cr
Gummite	General term for yellow, orange, red, or brown secondary minerals consisting of mixtures of hydrous oxides of uranium and thorium; an alteration product of uraninite
Iriginite	$U(MoO_4)_2(OH)_2.2H_2O$
Johannite	$Cu(UO_2)_2(SO_4)_2(OH)_2.6H_2O$
Kasolite	$Pb(UO_2)SiO_4.H_2O$
Meta-autunite	$Ca(UO_2)_2(PO_4)_2.26H_2O$
Metatorbernite	$Cu(UO_2)_2(PO_4)_2.8H_2O$
Meta-uranocircite	$Ba(UO_2)_2(PO_4)_2.8H_2O$
Monazite	$(Ce,La,Nd,Th)(PO_4,SiO_4)$
Phosphuranylite	$Ca(UO_2)_4(PO_4)_2(OH)_4.7H_2O$
Renardite	$Pb(UO_2)_4(PO_4)_2\,(OH)_4.7H_2O$
Sabugalite	$HA1(UO_2)_4(PO_4)_4.16H_2O$
Saleeite	$Mg(UO_2)_2(PO_4)_2.8H_2O$
Sklodowskite	$Mg(UO_2)Si_2O_7.6H_2O$
Soddyite	$(UO_2)_5Si_2O_9.6H_2O$
Thorogummite	$Th(SiO_4)_{1-x}(OH_4)_x$(may contain up to 31.4%U)
Thucholite	A complex of organic matter (hydrocarbons) and uraninite; usually contains thorium
Torbernite	$Cu(UO_2)_2(PO_4)_2.8\text{–}12H_2O$
Tyuyamunite	$Ca(UO_2)_2(VO_4)_2.5\text{–}8H_2O$
Umohoite	$(UO_2)MoO_4.4H_2O$
Uraninite	UO_2
Uranophane	$Ca(UO_2)_2Si_2O_7.6H_2O$
Xenotime	$(Y,Ce,Th,U)PO_4$

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

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