Critical review of acid in situ leach uranium mining: 1. USA and Australia

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Abstract The technique of in situ leach (ISL) uranium mining is well established in the USA, as well as being used extensively in Eastern Europe and the former Soviet Union. The method is being proposed and tested on uranium deposits in Australia, with sulfuric acid chemistry and no restoration of groundwater following mining. Test sites in the USA were required to restore groundwater to ascertain the extent of impacts and compare costs to alkaline ISL mines. The problems encountered include expensive and difficult restoration, gypsum precipitation, higher salinity and some heavy metals and radionuclides after restoration. One of the most critical issues is whether natural attenuation is capable of restoring groundwater quality and geochemical conditions in an acid leached aquifer zone. The history of acid ISL sites in the USA and Australia are presented in this study, with a particular focus on the demonstration of restoration of groundwater impacts.

Keywords Acid · In situ leach · Solution mining · Uranium plumes

Background

The unconventional mining technique of in situ leach (ISL) is now the primary producer of refined uranium in the United States, with a market share of around 95% in the mid 1990s (DoE 1999). The ISL technique, also known as 'solution mining', appears set to assume a new part of Australia's uranium industry.

It is an historical curiosity as to where the conceptual processes for ISL were first conceived and applied. The Chinese were apparently the first to use solution mining to produce copper as early as 907 A.D., with references to the technology dating back to 177 B.C. (Morris 1984). During the 1890s, the Frasch process for mining elemental sulfur was invented, and ISL mining of gold was first suggested by the Russians (Morris 1984). The first trials of uranium ISL were developed in the USA and the Soviet Union in the early 1960s. It is uncertain who developed the first projects or if they originated separately (Mudd 1998).

By the mid-1970s, there were uranium ISL mines across the world as alternative, potentially low cost producers (Larson 1981). In the USA, ISL mines generally used alkaline chemistry with only a few sites trialling acid chemistry. In contrast, Soviet mines generally used acid with only a few sites using alkaline reagents. In Australia during the early 1980s, two ISL projects at Beverley and Honeymoon in South Australia proposed acid while a third at Manyingee in Western Australia trialled alkaline chemistry. The Honeymoon site undertook an acid ISL trial in late 1982.

The environmental regulation of mining generally requires the restoration of affected groundwater to be returned to its pre-mining quality or use category. In countries controlled by the Soviet block, the need for restoration of contaminated groundwater following mining was ignored during operation, and the problems and magnitude of groundwater contamination, which are now coming to light in the 1990s, can only be described as extreme (Mudd 1998, 2001).

Indeed, the use of alkaline chemistry in the USA has been related to the need to restore affected groundwater and that alkaline mine sites are considered to be easier to restore (Tweeton and Peterson 1981; Mudd 1998). In direct contrast, Australian ISL projects – historically and currently – proposed not to restore affected groundwater after acid ISL mining.

The resurfacing of the Australian acid ISL uranium mine proposals in 1996 (because of a change in federal government and uranium policy), the lack of acid ISL mines in the USA, the research coming to light through the International Atomic Energy Agency (IAEA) and others of the extent of impacts from acid ISL mines in the Soviet block, led to a detailed review of ISL uranium mining (Mudd

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1998). The history and experience of acid ISL in Australia and the United States is reviewed herein, with the sites of the Soviet Block reviewed in the companion paper (Mudd 2001).

Acid ISL in the USA

Brief history of ISL

The initial development of ISL mining in the USA occurred in Wyoming at the Shirley Basin uranium project from 1961–1963 by the Utah Construction and Mining Company (now Pathfinder Mines Corporation; Larson 1981). They experimented with five generations of well-field design and over 100 patterns using sulfuric acid leaching chemistry (Underhill 1992). The Shirley Basin ISL project operated on a small scale from 1963–1969 to produce 577 t U (Underhill 1992); however, it was closed and converted to an open pit operation from 1970 (Larson 1981).

The late 1960s to mid 1970s witnessed rapid development and promise in ISL mining, principally in Texas and Wyoming (Kasper and others 1979). By May 1980, a total of 18 commercial and 9 pilot-scale projects were either in operation or under active development (Larson 1981). Virtually all of these sites utilized alkaline reagents such as ammonia- or sodium-carbonate/bicarbonate. The difficulty of restoring ammonia-based sites saw a quick shift in emphasis to sodium bicarbonate- or carbon dioxide-based leaching chemistry by the early 1980s (Tweeton and Peterson 1981). Despite years of lower production in the late 1980s, ISL mines have gradually increased their share of uranium production in the USA from about 1.2% in 1975 (Underhill 1992) to greater than 90% during the mid-1990s (DoE 1999).

By 1991, a total of 62 ISL projects had been developed, although only 24 of these sites were commercialized (Underhill 1992), indicating more unsuccessful than successful projects (Rojas 1987). There has been no development of a commercial ISL mine using acid chemistry since the Shirley Basin experimental project (Mays 1984). Further detail on all ISL mines is given by Mudd (1998). There were some sites in New Mexico, Texas and Wyoming, which underwent pilot-scale testing of acid ISL, compiled in Table 1, although most were poorly documented in the public literature (Mudd 1998).

The most documented acid ISL project is Nine Mile Lake near Casper, Wyoming. The project was developed by Rocky Mountain Energy Co. (RMEC) in association with research by the US Bureau of Mines. The landmark study was reported in detail by Nigbor and others (1981, 1982). RMEC's Reno Ranch acid ISL trial in Wyoming was reported by Staub and others (1986). Further acid ISL trial sites have not been reported widely in the literature. Although trialled at some sites, acid systems were generally considered unsuitable for Texan deposits because of higher carbonate (Hunkin 1977).

Nine Mile Lake, Wyoming

The geology and hydrogeology of the Nine Mile Lake (NML) site is given by Nigbor and others (1981, 1982) and Staub and others (1986). The following discussion is based on these references.

The NML uranium deposit is on the south-west flank of the Powder River Basin. The roll-front uranium mineralization occurs in the Teapot Sandstone within the Mesaverde Formation. The ore body extends over a strike length of 6,100 m in a north–north-west direction and ranges between 15 to 900 m in width, consisting of upper and lower zones. The site is at an elevation of 1,600 m. The uranium at NML was precipitated at the interface of oxidation–reduction boundaries in the Teapot sandstone because of the presence of carbonaceous material and pyrite. The principal uranium mineral was uraninite (UO_2), with minor quantities of coffinite ($USiO_4$); grades ranged from 0.04–0.12% U_3O_8. Vanadium was associated with the mineralization (range 0.1–0.4% V_2O_5), and was proposed to be extracted from a commercial facility. The ore zones contained less than 0.1% carbonate, although total carbon content was higher at 0.2–2.0%. The major clay mineral present was kaolinite (2–5%), with minor montmorillonite, although this had a low cation exchange capacity at 5 meq/100 g.

Because of the low carbonate content of the ore body and the low cost of sulfuric acid, NML was considered an ideal test site for acid ISL mining. Extensive laboratory tests on

Table 1
Pilot scale ISL mines using acid leaching chemistry from Staub and others (1986), Underhill (1992) and Mudd (1998)

Project/site	Company	Time period
Nine Mile Lake, Wyoming	Rocky Mountain Energy Co.	Mining: Nov. 1976 to Nov. 1980 Restoration suspended: Feb. 1982
Reno Ranch, Wyoming[a]	Rocky Mountain Energy Co.	Mining: Feb. 1979 to Nov. 1979 Restoration suspended: March 1981
Irigary, Wyoming	Wyoming Minerals	Unclear – acid trial referred to by Kasper and others (1979)
Jackpile Paguate, New Mexico[b]	Anaconda	Early 1970 trial, two well-fields, with two injection bores and 18 extraction bores, upgraded to 29. Project discontinued
Dunderstadt, Texas	Cities Service	Trial operated between 1969–1971. No reports
Besar Creek, Texas	Rocky Mountain Energy Co.	Early 1970s?, details unclear (plant later used at Nine Mile Lake)

[a] Also called Reno Creek
[b] Part of the North Windup Project

core samples suggested that savings in chemical costs would result from the use of acid. A total of four well-field patterns underwent testing and development at the NML project site. The chronology and detail for each pattern is summarised in Table 2.

Pattern 1, completed in the upper ore zone, experienced several problems that lead to poor operational performance. These included problems with the PVC well casing, cement baskets and pumps. A build-up of gypsum scale on the injection well screens, possibly related to the degradation of the casing cement by the acid, contributed to poor injectivity. Potential channelling and poor injectivity led to disappointing overall uranium recovery.

Pattern 2, completed in the lower ore zone, with a detailed assessment provided by Nigbor and others (1982), was considered a success. Injectivity was good, although plugging problems caused by 'fungus growth' and gypsum precipitation were encountered in April 1978. No evidence was provided to substantiate the 'fungus growth'.

The two injection bores of pattern 3 were completed in both the upper and lower ore zones to test the feasibility of simultaneously leaching both zones. The extraction bores were completed independently in each ore zone. The pattern experienced sporadic problems with well plugging, frozen lines and equipment failures, leading to poor operational performance. Further problems were encountered in controlling solution distribution to the two ore zones.

Pattern 4, using alkaline chemistry, was intended to give a comparison of alkaline and acid leaching on the same ore body. However, the results of this trial are not available although RMEC described it as "disappointing". No comparison can be made of the respective advantages and disadvantages of acid versus alkaline for this deposit.

There were five horizontal excursions detected at NML during testing, with three in pattern 3 and two in pattern 4. All excursions were bought under control by increasing the extraction rate. No monitoring of overlying and underlying bores was undertaken, and determination of any vertical excursions is not possible. This potential exists at every ISL mine because of casing failures and improperly sealed exploration bores (Marlowe 1984; Staub and others 1986). The risk increases with the total number of bores and age of a site (Marlowe 1984).

The restoration of each pattern was undertaken immediately after mining, followed by the regulatory period of monitoring to ensure the stabilization of groundwater quality. Post-restoration monitoring is critical in understanding the effectiveness of restoration efforts and long-term impacts on water quality at NML. The available baseline, leaching phase and restoration groundwater quality data for each pattern is compiled in Tables 3 and 4.

The restoration data is averaged from observation and extraction bores because of the tendency of injection bores to reflect the quality of injected solutions rather than groundwater after mixing in the aquifer. The high sulfate levels of the ore zone were thought to be related to influx from Nine Mile Lake itself, 1.6 km to the south, which is naturally high in sulfate.

The methods for restoring each pattern differed slightly. Pattern 1 was restored using a groundwater sweep, whereas pattern 3 involved a groundwater sweep combined with reverse osmosis treatment and mixed with 'clean' formation water before re-injection into the ore zone.

The post-restoration monitoring of pattern 1 from early 1978 to 1981 indicated substantial deterioration of water

Table 2
Research and development details for Nine Mile Lake. *Rest'n* Restoration

Pattern and type		Leaching solution chemistry	Period of testing[a]	PV[b]
1	Seven-spot, 15 m radius	4 g/l H_2SO_4 (pH 1.7), 0.5 g/l H_2O_2, 0.15 g/l $FeSO_4$, flow ~2.5 l/s	Mining: Nov. 1976 to Aug. 1977 Rest'n: Sep. 1977 to Oct. 1978	7 12
2	Five-spot, 15 m radius	3–5 g/l H_2SO_4 (pH 1.8), 1 g/l H_2O_2, flow ~2.6 l/s	Mining: Dec. 1977 to Sep. 1978 Rest'n: Sep. 1978 to Aug. 1979	13 12
3	Eight-spot[c], 18 m radius	H_2SO_4, H_2SO_5 or O_2, flow ~3.8 l/s	Mining: Sep. 1979 to April 1980 Rest'n: Aug. 1981 to Jan. 1982	5.6 6
4	Five-spot, 15 m radius	$Na_2CO_3/NaHCO_3$ with $CO_{2\ (g)}$ (pH~7.5), 0.5 g/l H_2O_2 (later) O_2	Mining: June 1980 to Nov. 1980 Rest'n: Nov. 1980 to Aug. 1981	? ?

[a] Restoration refers to initial phase only
[b] Aquifer pore volumes reached during testing
[c] Included two central injection and six extraction bores (effectively, one three-spot pattern for each ore zone aquifer)

Table 3
Baseline and restoration groundwater quality, patterns 1 and 3, Nine Mile Lake. All mg/l; except pH, EC in mS/m. From Staub and others (1986)

Pattern and phase		TDS	EC	pH	Cl	SO_4	Ca	U_3O_8	V
1	Baseline	2,483	316	6.9	3.3	1,240	87	0.384	0.1
	Restoration	7,750	1,200	6.9	93	5,140	300	0.289	0.073
3	Baseline	2,034	238	6.9	35	1,244	74	0.060	0.18
	Restoration	1,450	250	7.1	26	920	61	0.126	0.57

Table 4
Average baseline, leaching phase and restoration groundwater quality, with standard deviation, pattern 2, Nine Mile Lake (Nigbor and others 1981, 1982). Leaching values indicative only

	Units	Phase		
		Baseline	Leaching	Restoration[a]
TDS	mg/l	4,300±550		3,000 (2,390)
EC	mS/m	410±51	1,000–1,500	300 (308)
pH	–	6.7±0.3	1.5–2.0	6.1 (6.9)
Redox	mV	−120±200		−22 to 120
Diss. O_2	mg/l	1		<0.1
Cl	mg/l	46±4.3		29 (37)
SO_4	mg/l	2,510±244	Up to 8,000	1,585 (1,584)
HCO_3	mg/l	290±30		
F	mg/l	0.77±0.25		0.6
Ca	mg/l	207±43	260	805 (102)
Mg	mg/l	92±31		42
Na	mg/l	830±145		485
K	mg/l	14±3.6		6.2
Al	mg/l	0.13±0.05		
Fe	mg/l	1.07±0.4	Up to 200	6.8
Mn	mg/l	0.31±0.18		0.24
As	µg/l	40		24
B	mg/l	0.67±0.40		
Cr	mg/l	0.01		
Cu	mg/l	0.01		
Hg	mg/l	0.01		
Mo	µg/l	8±18		
P	mg/l	0.2		<0.1
Se	µg/l	2		13
Si	mg/l	4.2±4.0		14.8
V	mg/l	0.5±0.2	Up to 800	11.1 (0.986)
Zn	mg/l	0.02±0.02		1.97
^{226}Ra	Bq/l	18.9±1.1	370±6.3	
^{230}Th	Bq/l	0.0031±0.00019	1,813±118	
U	mg/l	0.23±0.10	80–150	1.05 (0.132)

[a] Includes additional restoration work undertaken in 1981–1982 in parentheses (Staub and others 1986)

quality because of gypsum dissolution increasing salinity levels. Reverse osmosis treatment of approximately 2.5 pore volumes of recirculated groundwater was undertaken in 1981, although later monitoring again showed deterioration and stabilization at a high salinity level. The water quality, with salinity four times higher at 7,750 mg/l and SO_4 three times higher at 5,140 mg/l, is now unsuitable for stock purposes – the pre-mining use category.

The restoration of pattern 2, however, proved to be more recalcitrant. The first phase of restoration involved 4 months of a modified groundwater sweep with re-injection of process water and barren production fluid. Restoration using reverse osmosis treatment was then undertaken for a month. From May to mid-August 1979, a high pH, sodium hydroxide solution was injected to promote ion exchange and speed restoration. Clean water recycling with reverse osmosis continued for the next 3 weeks, by which stage nearly all major parameters were restored to pre-mining ranges, and active restoration ceased.

Post-restoration monitoring of pattern 2 during late 1979 and early 1980 detected scattered areas of contaminated groundwater around the pattern interior, migrating slowly down gradient. Pumping resumed in August 1980, involving about 3.5 aquifer pore volumes, with the groundwater being treated with a lime/barium chloride precipitation process and re-injected into the well-field. Little improvement was apparent and, by May 1981, water quality was again deteriorating. As of June 1984, V, 226Ra and TDS remained above pre-mining levels.

The restoration of pattern 3 returned most parameters to baseline values or better but failed to restore U, V and ^{226}Ra to pre-mining levels.

The Nine Mile Lake acid ISL trial demonstrated that acid was indeed an effective leaching alternative to the alkaline chemistry prevailing at the time, albeit non-selective. Other issues raised by the trial include the difficulty in scaling laboratory test results to the field. The column leaching tests performed on NML core samples suggested significantly lower reagent consumption than that required in the field. The restoration of the laboratory columns indicated that about 13 pore volumes would be required to restore water quality, whereas in the field it was closer to 20 and still experienced deterioration after treatment efforts. Nigbor and others (1982) concluded that because of greater reagent consumption and the difficulty and expense of restoration acid leaching was no more cost effective than alkaline leaching.

The expansion of the NML site to commercial scale by RMEC proposed to use a seven-spot production pattern with a radius of 21 m, 3–5 g/l H_2SO_4 and 1 g/l H_2O_2 with V recovery. The site is yet to be developed.

Reno Ranch, Wyoming

The Reno Ranch (Reno Creek) uranium deposit in Wyoming, although lesser known than the Nine Mile Lake site, underwent a trial of acid ISL at about the same time period. An alkaline six-spot trial was also developed. Unlike NML, however, the geology, hydrogeology and information on both the acid and alkaline ISL trials at Reno Ranch was published by Staub and others (1986).

Reno Ranch is on the eastern flank of the Powder River Basin. The roll-front uranium mineralization occurs in the Wasatch Formation, consisting of fluvial sandstones, siltstones, shales, claystones and coal seams. The ore zone contains high quantities of carbonate minerals, although quantitative data are unavailable. The site is at an elevation of 1,590 m.

Two well-field patterns were developed and tested, the first being a conventional five-spot pattern and the second being a six-spot pattern with two injection and four extraction bores. Pattern 1 was leached with acid whereas pattern 2 with alkaline reagents, details are in Table 5. Results for the two patterns are in Tables 6 and 7, respectively.

After mining was initiated in pattern 1, problems with gypsum precipitation and ‘fungus growth’ reduced the efficiency of well field circulation. No evidence was provided for the ‘fungus growth’. The uranium recovery rates were low and the carbonate minerals in the host sandstone consumed high quantities of acid. Leaching was terminated prematurely and restoration began immediately, consisting of water treatment by ion exchange, groundwater sweeping and treatment with potassium carbonate to

Table 5
Research and development details for Reno Ranch. *Rest'n* Restoration

Pattern and type		Leaching solution chemistry	Period of testing	PV
1	Five-spot, 12 m radius	5 g/l H_2SO_4 (pH 1.8), H_2O_2, flow ~2.5 l/s	Mining: Feb. 1979 to Nov. 1979	?
			Rest'n: Nov. 1979 to Oct. 1981	?
2	Six-spot[a], 15 m radius	Na_2CO_3/$NaHCO_3$, H_2O_2, flow ~1.6 l/s	Mining: Sep. 1980 to Dec. 1980	?
			Rest'n: Dec. 1980 to April 1981	6.5

[a] Included two central injection and four extraction bores

Table 6
Range of baseline, leaching phase and restoration groundwater quality in the Reno Ranch ore zone for pattern 1 (acid). All mg/l; except pH; EC in mS/m. From Staub and others (1986). *Mon./Prod.* Monitoring/production bores; *ND* Not detectable

	Baseline		Leaching Range	Restoration Feb. 1981	Post-restoration[a]	
	Average	Range			Mon.	Prod.
TDS	1,176	283–1,597			1,267	2,551
EC	155	122–200				
pH	8.1	6.4–12.2	2.7–7.6	4.9	9.3	5.3
HCO_3	91	ND–305				
CO_3[b]	50	ND–281				
Alk.[c]	89	ND–225				
SO_4	588	11–1,006	981–3,928	1,482	764	1,551
Cl	24	6–66				
F	0.46	ND–0.57				
NH_4	0.4	ND–16.8				
NO_3	0.5	ND–7				
Na	228	87–322				
K	11.3	5–29				
Ca	104	72–203	156–666	217	102	263
Mg	21	1–51				
Fe	1.0	ND–3	<0.1–242	38.5		
Al	0.55	ND–1.45				
As	0.02	ND–0.03				
B	0.9	ND–2.6				
Mn	0.05	ND–0.22				
Se	0.02	ND–0.05				
SiO_2	5.7	ND–8.7				
U_3O_8	0.46	0.001–2.0	<0.1–22.0	1.4	0.059	0.64
V	<1.0	0–8	<0.1–9.0	0.4		

[a] Post-restoration groundwater quality in March 1983
[b] As CO_3
[c] Alkalinity as $CaCO_3$

Table 7
Range of baseline, leaching phase and restoration groundwater quality in the Reno Ranch ore zone for pattern 2 (alkaline). All mg/l, except pH; EC in mS/m; ^{226}Ra in Bq/l. (Staub and others 1986)

	Baseline		Leaching Range	Restoration Post-leach	Post-restoration	
	Average	Range			Post-IX	Post sweep
TDS	1,438	1,384–1,506				
EC	199	189–223	350	340	200	199
pH	8.9	8.4–9.5	7.2	7.4	7.7	7.7
HCO_3	84	11–178	1,800	1,670	160	125
CO_3[a]	9.9	2–32				
Alk.[b]	80	45–109				
SO_4	918	890–975				
Cl	10.4	7.0–18.8	240	113	19	15
Na	296	273–360	900	770	305	322
K	13.8	7.4–44				
Ca	119	102–153	330	207	69	87
Mg	21	12–26				
Fe	–	0.03–0.61	8.0	0.6	0.16	0.39
^{226}Ra	–	3.9–28.4		11.5	8.8	8.2
U_3O_8	0.049	0.007–0.287	65	16	1.64	1.37
V	0.07	0.04–0.34	6	3	1.05	0.45

[a] As CO_3
[b] Alkalinity as $CaCO_3$

raise the pH and facilitate further removal of calcium, heavy metals and radionuclides. The restoration sequence, although aggressive compared to other efforts at ISL mine sites, encountered many difficulties.

The ongoing restoration efforts of pattern 1 failed to reduce free acidity, SO_4 and ^{226}Ra levels. RMEC proposed the use of a high salinity solution to displace the hydrogen ions from clay lattice structures, enabling these to be removed during the restoration process. The regulatory agencies refused this technique because of uncertainties and possible adverse effects on the aquifer and groundwater quality.

Very little post-restoration water quality improvement has occurred at pattern 1. During the first quarter of 1983, groundwater monitoring indicated that pH levels in the aquifers have not improved significantly, Ca and SO_4 concentrations have not changed significantly (270 and 1,500 mg/l, respectively), U levels have decreased marginally to less than 1.0 mg/l, and TDS ($\sim$2,650 mg/l) remains almost twice that before mining.

Pattern 2, leached with alkaline reagents, proved less problematic from an operational and restoration perspective; however, post-restoration monitoring indicated a significant increase in U concentration from 2.0 mg/l in April 1981 to 3.7 mg/l in February 1983. In comparison, the pre-mining U concentration was 0.23 mg/l. This pattern of increasing uranium concentrations after restoration has been noted at many restored ISL sites (Staub and others 1986). The V concentrations also remained significantly higher after mining and restoration efforts.

There were no reported excursions at the Reno Ranch site, although it was questionable whether the control limits were sensitive enough to detect such an event, especially for a vertical excursion. From a restoration perspective, the difference in post-restoration groundwater quality between acid and alkaline leaching appear minimal because both patterns experienced higher concentrations of some metals or radionuclides. The use of acid tends to exacerbate the concentrations of calcium and sulfate in groundwater, despite aggressive restoration efforts. As with Nine Mile Lake, the Reno Ranch site is yet to be commercialized, and new interest in the development of the deposit has been recently abandoned.

Acid ISL in the USA – summary

The experience with acid ISL uranium mining at Nine Mile Lake and Reno Ranch has shown that it can be an alternative, albeit non-selective, to the alkaline process. The choice, however, presents two major potential problems: (1) precipitation of gypsum on well screens and within the aquifer during mining, plugging wells and reducing the formation permeability (critical for economic operation); and (2) gradual dissolution of the precipitated gypsum following restoration, leading to increased salinity and sulfate levels in groundwater. The further effects of the release of heavy metals and radionuclides, especially ^{226}Ra, which were co-precipitated with the gypsum, have not been assessed or quantified. A critical issue is that acid leaching was not found to be more cost effective than alkaline, when taking restoration into consideration. No commercial acid ISL uranium mine has yet been approved or developed in the USA and it remains unlikely in the near future.

Acid ISL in Australia

Brief history

The history of ISL uranium mining in Australia coincides with public concern regarding the environment, nuclear issues and indigenous land rights. Three sites have had pilot scale testing – two with acid, at Beverley (1998) and Honeymoon (1982 and 1998–2000) in South Australia, and one with alkaline chemistry at Manyingee (1985) in Western Australia. A location of Australian ISL deposits is shown in Fig. 1, with potential projects given in Table 8. There has been no commercial acid ISL copper mine, although several sites near Mt Isa, Queensland, have undergone trials in the late 1960s to mid 1970s (Bell 1984). More recently a variant of stope leaching was tested at the Gunpowder (Mammoth) copper mine (see Landmark 1992; Middlin and Meka 1993). A small experimental acid ISL copper project was trialled at the old Mutooroo mine, 100 km south of Honeymoon, during 1981–1982 (Bampton and others 1983). All projects proved difficult and subeconomic, and thus commercial acid ISL copper mining is yet to be realized in Australia.

A different site of note was the Western world's first proposed ISL gold mine at Eastville, central Victoria, in the early 1980s by mining company CRA Ltd (Bell 1984). The project planned to solution mine the deep alluvial gold leads by cyanide leaching chemistry (Hore-Lacy 1982). The community and regulators, however, expressed concerns about possible groundwater contamination arising from the use of cyanide in the rural farming area. After some initial hydrogeological pump and dye tracer tests (Hore-Lacy 1982), regulatory approvals were rejected (Bell 1984) and CRA later abandoned the project.

The use of solution mining has also been applied to potash mining in Western Australia, as well as for potential use in several other locations around Australia (Hancock 1988).

The Beverley and Honeymoon uranium deposits, in the Lake Frome Embayment in north-eastern South Australia, were discovered in the early 1970s at a time when the prospects for nuclear power and uranium mining seemed promising. The Beverley project was originally planned as an open pit operation but was shelved in 1974 as subeconomic. The Honeymoon deposit, however, was recognized to be uneconomic by conventional mining from the outset, and by the late 1970s, ISL was being investigated as a possible economic alternative.

Alkaline push–pull tests were first conducted at Honeymoon in 1977 using ammonia-bicarbonate solutions, and results were disappointing (Dobrowolski 1983). A second push–pull test using sulfuric acid was undertaken in 1979, giving positive results and the companies proceeded towards commercial development (Dobrowolski 1983). The Draft and Supplementary Environmental Impact Statements (EIS) were prepared (MINAD 1980, 1981) with

Fig. 1
Location of uranium deposits in Australia amenable to ISL

Table 8
ISL-amenable uranium deposits in Australia. References updated from recent company reports, Dunn and others (1990), Johns (1990), Mudd (1998)

Deposit	Discovered	t U_3O_8	Grade	Company (and country)
Manyingee, WA	1974	12,078	0.08%	Paladin Resources Ltd (Australia)
Oobagooma, WA	1978	9,950	0.12%	Paladin Resources Ltd (Australia)
Bennett's Well, WA	1983	1,500	0.16%	Eagle Bay Resources NL (Australia)
Honeymoon, SA	1972	3,900	0.12%	Southern Cross Resources Inc. (Canada)
East Kalkaroo, SA[a]	1970	4,000	0.10%	Southern Cross Resources Inc. (Canada)
Gould's Dam, SA	1974	17,640	0.098%	Southern Cross Resources Inc. (Canada)
Beverley, SA	1969	21,000	0.18%	General Atomics (USA)
Paralana-Pepegoona, SA	1970	1,000	0.2%	General Atomics (USA)
Angela, NT	1974	12,000	0.1%	Black Range Minerals (Australia)

[a] Includes Yarramba deposit

federal government approval being obtained in late 1981 for pilot testing before commercial scale operations could proceed (Mudd 1998). A semi-commercial scale pilot plant, with a capacity of about 115 t U_3O_8/year, was built and operated briefly in 1982 but was plagued with operational problems because of jarosite precipitation and other issues (Mudd 1998).

The companies developing the Beverley deposit first investigated the use of ISL in about 1980, releasing their Draft EIS in 1982 (SAUC 1982). No Supplementary EIS was released and the environmental assessment process was not completed, however, and final approvals could not be given. Both projects proposed not to restore mining affected groundwater following the cessation of operations at each site, despite the acknowledged impacts on pollutant loads. In March 1983, the recently elected government of South Australia refused to issue mining leases for commercial operations at Beverley and Honeymoon, citing four reasons (Mudd 1998): (1) many of the economic, social, biological, genetic, safety and environmental problems associated with the nuclear industry were unresolved; (2) endorsement of the Government's position by a wide range of community organizations; (3) commitment to the Roxby Downs (Olympic Dam) project; and (4) community unrest at the nature of the ISL process. The later introduction of the federal 'Three Mines Uranium Policy' in 1984 saw no further development until the election of a new federal government in 1996 and the immediate removal of this policy (Mudd 1998). The Honeymoon site was joined with all nearby deposits, including Gould's Dam 75 km north-west.

Further detail on the geology of ISL-type uranium deposits and their formation in the Lake Frome region is given by Callen (1975), Haynes (1975), Brunt (1978), Ellis (1980), Morris (1984), Johns (1990), Curtis and others (1990) and Hobday and Galloway (1999). The following discussion uses these references, except where noted.

Beverley ISL project

The Beverley deposit was discovered by the Oilmin–Transmin–Petromin (OTP) Group of companies in 1969, with drilling in 1970 confirming economic uranium grades (Mudd 1998). After nearly three decades and two unsuccessful attempts, the Beverley uranium deposit finally began development in 1996 towards a commercial operation through new owner Heathgate Resources Pty Ltd (HR), a wholly-owned Australian subsidiary of US-based General Atomics Corporation.

The geology and hydrogeology of Beverley is given in SAUC (1982) and HR (1998a). The 100 to 140 m of overburden consists of alluvial fans comprising lenses of gravels, sands, silts and clays. The uranium mineralization occurs within semi-isolated aquifer sands that resemble a concealed fluvial system or palaeochannel. The deposit contains three ore zones – Northern, Central and Southern, each with increasingly higher salinity, respectively. Beneath the ore zone aquifer is a thick mudstone sequence and the Cadna Owie sandstone of the Great Artesian Basin at 300 m depth. The hydrogeological relationships in the area are complicated by structural deformation and faulting, which may provide vertical interconnection between the deeper aquifers, while possibly truncating aquifers in the shallower sediments (Hancock 1986). A regional hydrogeological cross section is shown in Fig. 2. The potential for improperly sealed exploration boreholes (from the time when Beverley was planned as an open pit mine) to increase the risk of excursions has been recognized (Hancock 1986, 1988), although downplayed in more recent times.

A series of new groundwater bores were installed in 1996 and 1997, including two five-spot patterns, and hydrogeological pump testing was completed. HR applied for the operation of an acid ISL trial in late 1997 with no proposed groundwater restoration. The trial began on 2 January 1998 (before public release of a new EIS for the project) and was to leach the five-spot patterns in the Northern and Central ore zones, each for about 6 months.

After the release of the new EIS in July 1998, further studies were required by regulators to address outstanding uncertainties, such as the degree of isolation of the Beverley aquifer, long-term impacts on groundwater quality, and especially the potential to contaminate surrounding groundwater systems. HR still proposed not to restore affected groundwater following current and future mining operations. With completion of these extra studies, final government approvals were received in April 1999 with conditions on liquid waste disposal.

The significant outcomes of the approvals process for Beverley include (1) it is the Western world's first commercial scale acid ISL uranium mine (OECD, 2000), (2) it proposes to re-inject all liquid wastes back into the mined aquifer rather than deep re-injection (»1 km; as per some US sites) or evaporation (as per most US sites), (3) the extent of the palaeochannel system is underexplored beyond the surrounds of the three ore zones, and (4) it is the first mining project in modern Australian history not required to restore the majority of its environmental impacts after cessation of operations (that is, groundwater contamination).

HR (1998a, 1998b) argued that following mining, the levels of radionuclides, heavy metals and pH will return to pre-mining conditions given several years; no mechanism was provided. This deserves critical assessment. The ore contains low sulfide (0.13%), organic carbon (0.05%), carbonate (0.06%), Fe, Mn and clay content (Hancock 1986, 1988; HR 1998a). Hancock (1986, 1988) argued that the exchangeable and soluble calcium and carbonate in the clays and sands surrounding the ore zones would be sufficient to neutralize the residual acid from migrating mining solutions and therefore precipitate gypsum. Because of the minimal degree of exploration data beyond the confines of the ore zones, however, this hypothesis remains untested and no data have been released to demonstrate this mechanism would perform satisfactorily at Beverley.

Buma (1979) argued that natural geochemical processes within aquifers can restore ISL-contaminated groundwater, thereby saving valuable chemical, energy and financial resources. The processes include precipitation of reduced compounds; scavenging of heavy metals by pyrite, organic matter, calcite and ferric oxyhydroxides; and adsorption by quartz, feldspars and clays. The key was for active reductants to be present. The conditions at Beverley, therefore, fail to provide any geochemical mechanism for natural restoration following acid ISL mining (because of the low abundance of active reductants). The 2-year-old trial site, if the data were to be published, might be able to shed important light on such behaviour.

Of further significance is that "reliance on this process (natural restoration) has never been tested" (Morris 1984). The time required and the rates at which natural geochemical processes could attenuate such levels of pollution are yet to be firmly established (Rojas 1987). The extreme levels of groundwater contamination wrought at acid ISL uranium mines across the Former Soviet Union suggests natural restoration appears to be spurious at worst, and ineffective at best (Mudd 2001).

The potential for excursions because of abandoned exploration bores still remains, as well as excursions caused by well casing failures (Marlowe 1984). Curiously, final approvals for Beverley included provisions that liquid waste re-injection only occur in the Northern zone – the zone of least exploration drilling and, importantly, the region of the best quality groundwater (TDS ~3–6 g/l). This zone has similar water quality to pastoral use in the region (excluding radionuclides), although numerous mines in Western Australia often operate with much more saline groundwater (TDS up to 250 g/l).

The high Ca and SO_4 levels of the Beverley ore zones, especially the Central and Southern ore zones, create the potential for gypsum precipitation (see Tables 9, 10 and 11). This creates potential problems similar to Nine Mile Lake and Reno Ranch, both operationally and for post-mining geochemical conditions.

By August 1998, HR had apparently begun leaching of the Central trial pattern, although the full results from the

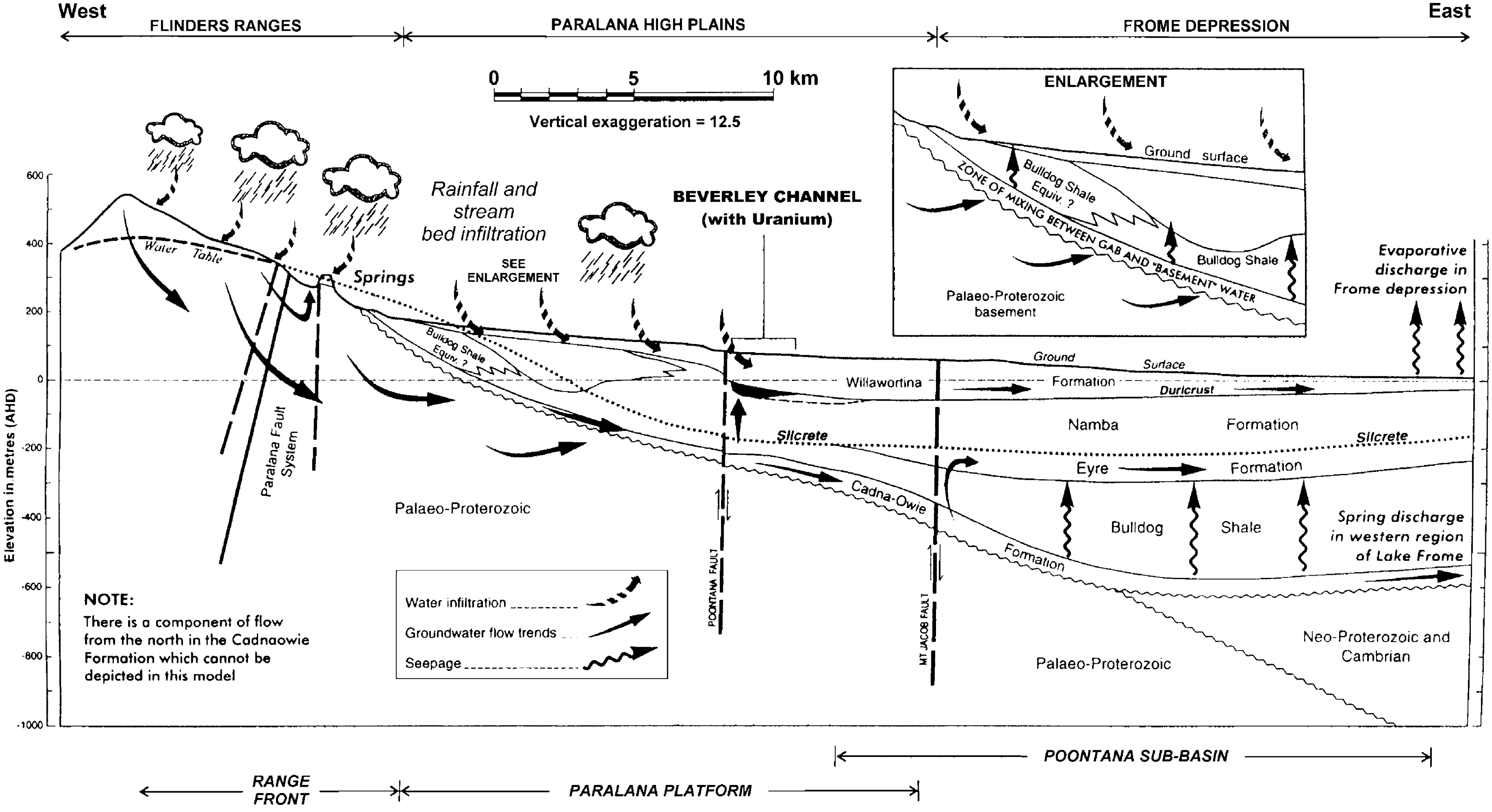

Fig. 2
Regional hydrogeological cross section of the Beverley deposit and region (HR 1998a)

Northern trial are yet to be published. This contrasts to the USA regulatory process where the results and restoration of a pilot scale facility form the permitting basis of a commercial mine (Kasper and others 1979). The construction of the commercial acid ISL mine at Beverley proceeded during 1999 and 2000, achieving operational status in late 2000.

Honeymoon ISL project

The Honeymoon deposit was Australia's first attempt at developing an ISL uranium mine. It is within the Yarramba palaeochannel, consisting of three distinct sands separated by thin, discontinuous clay layers. The Upper aquifer is occasionally used by pastoralists in the region while the Basal sand contains the uranium deposit. Traces of uranium mineralization exist in all three sands, with the Yarramba deposit to the north located in the Middle sand. The hydraulic head is identical for all three sands, suggesting a high degree of vertical interconnection. A hydrogeological cross section is shown in Fig. 3.

The deposit has several unique features related to the use of ISL, including pyrite content at 5–15%, compared with less than 2% in most USA deposits; higher salinity; low organic content (0.3%); and direct hydraulic connections between the three aquifers in the palaeochannel because of gaps in the clay-confining layers. A compilation of groundwater and solution quality is given in Table 12.

By mid-1982, the solvent extraction pilot plant and four five-spot patterns had been constructed (the fourth pattern intersected silt lenses with little or no uranium), and an ISL trial started using sulfuric acid and ferric sulfate as an oxidant. The trial encountered significant operational failure as a result of, principally, jarosite precipitation. The details have never been published, although it is known that preventing jarosite formation was difficult (Mudd 1998).

The new Canadian owners gained approval for a new trial at Honeymoon in March 1998, relying mainly on previous EIS approvals. The work began in April 1998 and continued through to August 2000. The new work is focused on trialling oxygen as the oxidizing agent, which should minimize the potential for jarosite formation, although other reagents, including hydrogen peroxide and ferric sulfate, are being tested. Detailed information from both the 1982 and new trial was not incorporated in the new EIS for the project, released in June 2000 (SCRA 2000a).

The approvals for Beverley set important precedents for ISL in Australia that have critical implications for the Honey-

Table 9
Groundwater and solution quality at Beverley: northern, central and southern ore zones, northern field leach trial data (injection and extraction averages March to July 1998) and Retention Pond (July 1998). Compiled from HR (1998a, 1998b), SAUC (1982). *n.a.* Not available

	pH –	TDS (g/l)	S (g/l)	SO_4 (g/l)	Cl (g/l)	F (mg/l)	Na (g/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)
Northern	7.3	3–6	n.a.	1.6	2	0.85	1.2	42	380	198
Central	7	6–10	n.a.	2.1	n.a.	n.a.	n.a.	n.a.	610	n.a.
Southern	6.8	11–13	n.a.	2.6	n.a.	n.a.	n.a.	n.a.	850	n.a.
Injection	1.93	11.5	1.6	4.79	2.0	7.67	1.43	59	610	337
Extraction	1.97	11.7	1.6	4.84	2.0	7.33	1.43	59	600	337
Ret. Pond	2.10	62.1	9.8	29.5	6.1	5.50	15.1	105	460	369

Table 10
Groundwater and solution quality at Beverley: northern, central and southern ore zones, northern field leach trial data (injection and extraction averages March to July 1998) and Retention Pond (July 1998). Compiled from HR (1998a, 1998b), SAUC (1982). *n.a.* Not available

	Al (mg/l)	Fe (mg/l)	Mn (mg/l)	Si (mg/l)	SiO_2 (mg/l)	U (mg/l)	Ra^{226} (Bq/l)	Rn^{222} (Bq/l)
Northern	0.2	0.7	0.2	48	n.a.	0.076	22–967	500–2,000
Central	n.a.	n.a.	n.a.	n.a.	n.a.	1.91	1.2–3,100	5–32,140
Southern	n.a.	n.a.	n.a.	n.a.	n.a.	0.70	13–111	20–585
Injection	91	109	0.7	138	294	2.9	8,414	n.a.
Extraction	91	105	0.8	133	283	162	9,881	n.a.
Ret. Pond	39	39	0.9	99	211	272	1,713	n.a.

Table 11
Groundwater and solution quality at Beverley: northern, central and southern ore zones, northern field leach trial data (injection and extraction averages March to July 1998) and Retention Pond (July 1998). Compiled from HR (1998a, 1998b), SAUC (1982). *n.a.* Not available

	B (mg/l)	Ba (µg/l)	Cd (µg/l)	Co (mg/l)	Cr (µg/l)	Cu (µg/l)	Ni (mg/l)	Pb (µg/l)	Se (µg/l)	V (µg/l)
Northern	1.6	53	0.2	0.1	20	30	0.004	40	1	1
Injection	1.0	37	117	20	100	200	8.47	160	410	1,100
Extraction	1.1	39	116	20	580	200	8.33	790	410	1,130
Ret. Pond	3.4	76	49	6.6	260	180	2.48	70	310	780

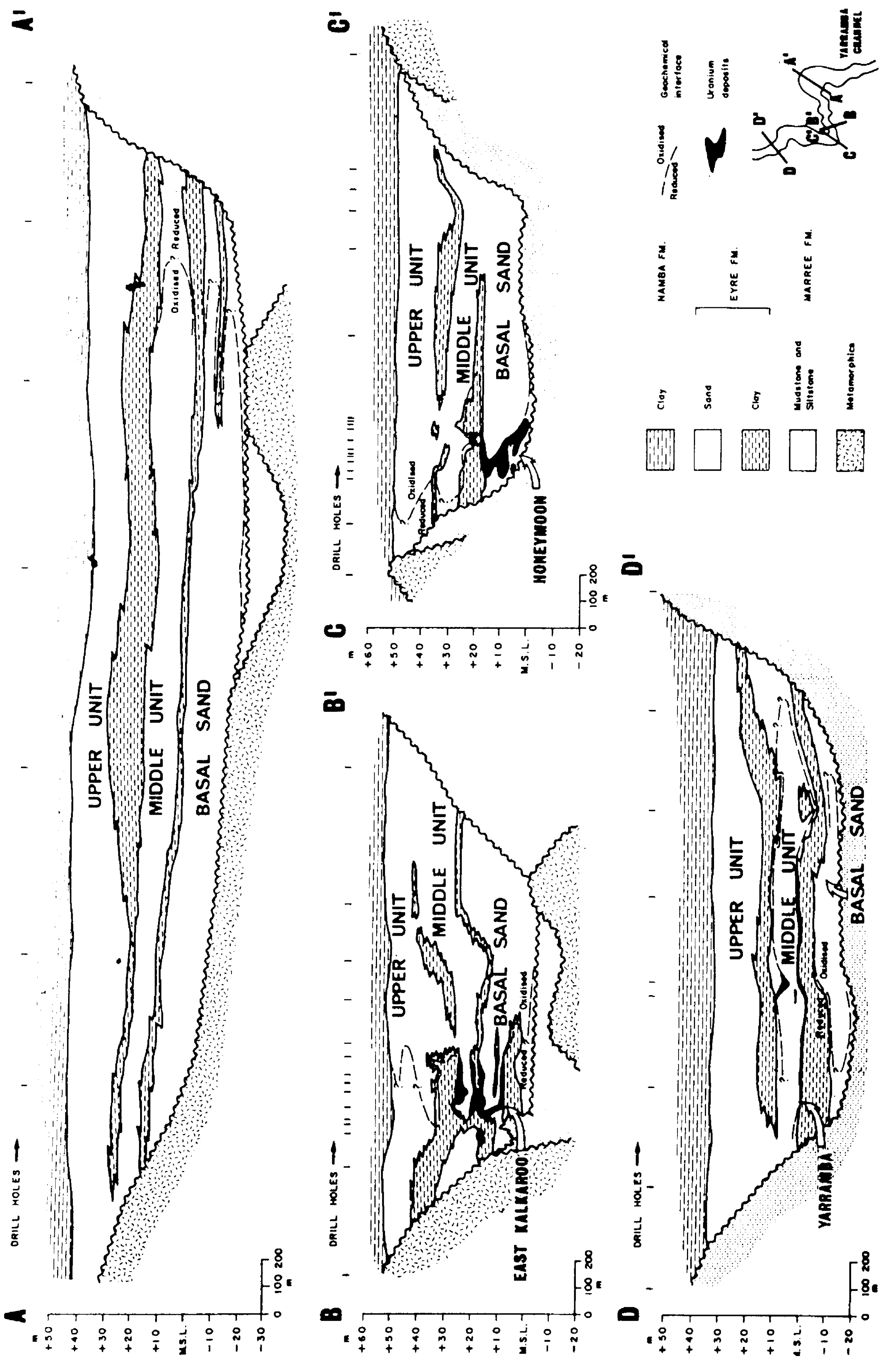

Fig. 3
Hydrogeological cross sections of the Yarramba Palaeochannel and the Honeymoon, East Kalkaroo and Yarramba uranium deposits (Brunt 1978)

Table 12

Groundwater and solution quality at Honeymoon (mg/l). Compiled from Bush (1999); SCRA (2000a, 2000b; Pirlo (2000). Units all mg/l, ^{226}Ra, ^{222}Rn and ^{210}Pb in Bq/l. *Org. C* Organic carbon; *Disposal* waste liquids for re-injection or surface evaporation; *RO brine* Rejected saline water from the water treatment (reverse osmosis) plant

	Basal sand aquifer		Middle sand aquifer		Upper sand aquifer		Acid leaching solutions		Disposal solutions	RO brine Average
	Average	Range	Average	Range	Average	Range	Average	Range		
Salinity	16,100	9,400–20,000	11,400	10,000–12.900	10,100	10,000–11,000	16,430	15,300–20,000	19,800	23,000
pH	6.9	6.5–9.1	7.0	6.7–8.9	7.5	7.0–8.0	2.2	1.8–2.6	1.8–2.8	6.8
Na	4,310	2,820–5,250	3,385	2,335–3,600	2,809	2,570–3,010	6,170	5,150–7,200	5,600	6,190
K	20.7	18.5–22.5	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	27.5	n.a.
Ca	906	100–1,480	560	480–710	478	440–545	940	810–1,050	1,000	1,040
Mg	390	200–560	270	85–390	260	245–297	210	90–460	430	600
Fe	1.0	<1.0–1.0	1.0	<1.0–1.0	1.0	<1.0–1.0	260	110–370	200	<1
Al	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	15	0.2–70	28.3	<1
SO_4	1,754	1,080–2,670	1,540	1,130–1,860	1,445	1,360–1,611	5,300	3,580–6,800	6,110	3,410
Cl	7,850	4,020–9,740	5,370	4,710–6,260	4,800	4,610–5,220	8,470	7,650–9,760	8,020	10,500
HCO_3	145	90–270	160	28–210	187	179–210	<5	<5	<5	270
Org. C	1.2	1–3	n.a.	n.a.	n.a.	n.a.	2	1–25	n.a.	n.a.
F	0.5	<0.5–1.1	0.5	<0.5–1.8	0.8	0.05–1.2	0.6	0.3–0.9	1.9	1.8
NO_3	0.3	0.1–1.4	0.9	0.1–1.6	0.1	<0.1–0.1	<0.5	<0.5	<0.5	<0.5
SiO_2	7.6	4.8–9.8	6.4	4.8–9.4	6.5	5.5–7.4	n.a.	n.a.	101	15
Co	0.060	0.045–0.80	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	2.2	n.a.
Cr	0.02	0.02–0.02	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.10	n.a.
Cu	0.02	0.01–0.12	0.03	0.01–0.1	0.008	0.005–0.010	7	1–20	1.8	0.01
Mo	0.013	0.001–0.040	0.010	0.007–0.020	0.009	0.007–0.011	0003	<0.0005–0.010	0.0074	0.022
Ni	0.078	0.060–0.105	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	3.53	n.a.
Se	0.030	0.013–0.075	0.019	0.010–0.030	0.014	0.011–0.022	0.055	0.040–0.070	0.079	0.036
V	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	4	2–8	1.1	<0.02
Zn	0.19	0.03–0.67	0.2	0.02–1.1	0.20	0.03–0.46	110	80–130	56.3	0.09
U_3O_8	1.2	0.007–7.3	0.018	0.001–0.035	0.022	0.007–0.045	75	20–1,000	1.5–3.0	0.16
^{226}Ra	205	22–450	7	0.2–17	3.1	0.2–6.6	830	510–1,300	130–680	3.0
^{222}Rn	5,000	3,100–6,800	7	6–10	23	15–30	12,700	n.a.	n.a.	n.a.
^{210}Pb	0.8	0.02–3.1	6.6	1.9–17.0	3.6	0.3–6.8	n.a.	n.a.	560	3.8

moon project: (1) the project proposes to re-inject all liquid wastes into the palaeochannel – but still into the lower aquifer, which is known to be hydraulically connected to the Upper aquifer occasionally used by pastoralists; (2) the potential for ‘natural restoration’ is uncertain, although this depends on the reactivity of pyrite (or other reductants) remaining after mining; and (3) the Yarramba palaeochannel is the only groundwater resource in the region (the velocity is about 18 m/year; MINAD 1980).

Pirlo (2000) investigated the potential geochemical reactions in groundwater, leaching and wastewater solutions through modelling of water chemistry. This was based on samples of groundwater from the Honeymoon and East Kalkaroo ore zones plus a sample of wastewater from the Honeymoon trial mine. No field measurement of redox potential was undertaken (this was calculated by the geochemical model REACT using Zn^{2+}/ZnS). Although mixing of the various solutions suggested that precipitation effects in the aquifer would be minimal and that heavy metals would not remain mobile after sufficient dilution, Pirlo (2000) acknowledged that kinetic effects are not incorporated in this mixing approach. No directly measured evidence from the trial or the analysis by Pirlo (2000), especially concerning the redox state in the aquifer, demonstrates that natural attenuation has or will work at Honeymoon, with no rates or timeframe established for such processes.

The potential for post-mining impacts on groundwater remain significant, especially if restoration is again not required by government regulators. Final regulatory approval for Honeymoon has been withheld until these and other issues have been adequately addressed by the current proponent.

Discussion and conclusions

The use of acid ISL in the USA was considered problematic and has never been approved or used on a commercial scale, despite the lengthy research at Nine Mile Lake and Reno Ranch, Wyoming. The problems included higher salinity and some radionuclides in post-restoration monitoring of groundwater compared with pre-mining conditions. In Australia, the results from acid ISL trials at Beverley and Honeymoon have never been sufficiently published and thus information is limited on their impacts. Critically, the issues of geochemical conditions in the groundwater following mining have not been satisfactorily addressed, with no clear evidence of natural attenuation at either site. The current configuration of the Beverley and Honeymoon projects – acid leaching with no restoration of polluted groundwater – is more akin to practices in Eastern Europe and the Former Soviet Union, where the available evidence suggests that natural attenuation fails to reduce the impacts from such mines (Mudd 1998 and 2001). The standards applied at the Australian sites are not considered an acceptable approach for an arid region that is almost entirely dependent on groundwater.

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