Environmental hydrogeology of in situ leach uranium mining in Australia

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Abstract. The use of the 'in situ leach' technique of uranium mining is a new development in Australia's expanding uranium industry. To date there have been three sites of pilot leach mines at Beverley (1998) and Honeymoon (1982, 1998-2000) in South Australia and at Manyingee (1985) in Western Australia. The Beverley and Honeymoon projects gained regulatory approvals in early 1999 and late 2001, respectively. The principal concerns with solution mining relate to impacts on groundwater and whether this naturally attenuates or requires active restoration. These environmental hydrogeological issues are reviewed in detail.

Overview of In Situ Leach Uranium Mining in Australia

Until recently, Australia had a short and mostly experimental history with in situ leach uranium mining, also known as solution mining (Mudd 2001a). Pilot scale testing has been undertaken at three deposits: Honeymoon (1982, 1998-2000), Beverley (1998) and Manyingee (1985; locations shown in Fig. 1). The recent approvals of Beverley and Honeymoon as commercial mines has allowed the technqiue to become a part of Australia's expanding uranium industry.

The Beverley mine began commercial operations in late 2000 with production of 219 and 327 t U_3O_8 in the June and December halves of 2001. The Honeymoon project, which now also includes the adjacent East Kalkaroo deposit, obtained regulatory approvals in late 2001 and is currently planning and moving towards construction. Commercial operation is expected by early 2003. The Manyingee deposit, however, is still being re-assessed (slowly) with no firm plans.

The various pilot mines operated at all three sites were developed to investigate both commercial and engineering requirements as well as the groundwater impacts and necessary management strategies, such as pH control to minimise mineral precipitation. No pilot site was required to restore impacted groundwater. The specific hydrogeological and environmental impacts of each site is now reviewed.

Fig. 1. Location of potential in situ leach uranium mines in Australia (Mudd 2001a)

Beverley, South Australia

The Beverley project, owned by General Atomics of the USA, has succeeded in becoming Australia's first commercial acid-based in situ leach uranium mine. For a broader history of Australian in situ leach mines (Cu, Au) see Mudd (1998, 2001a) and for the Beverley project's development history HR (1998a, b) and Mudd (1998, 2001a).

Geology and Hydrogeology

The geology and hydrogeology of the Beverley uranium deposit is described by Haynes (1975), SAUC (1982), HR (1998a, b) and Mudd (1998, 2001a).

Located in the western part of the Frome Embayment, the deposit is overlain by about 100 m of alluvial fans comprising lenses of gravels, sands, silts and clays. The uranium mineralisation occurs within 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 hydrogeology is 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. A plan of the ore zones is shown in Fig. 3. A compilation of groundwater quality is given in Table 1.

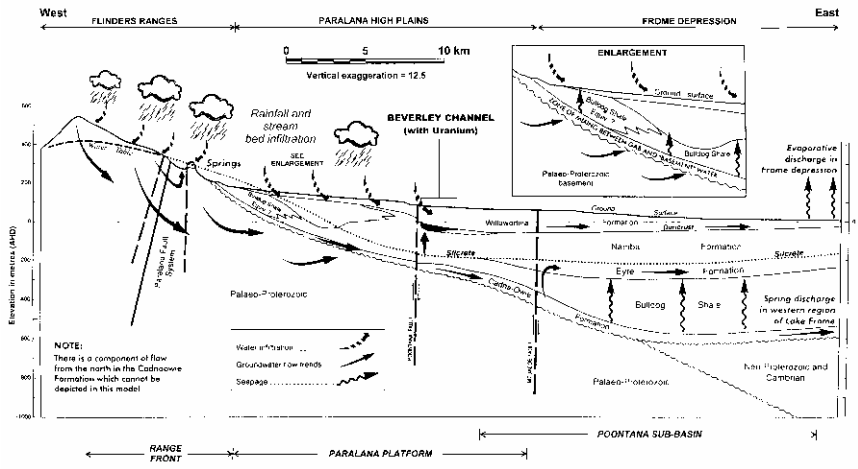

Fig. 2. Regional hydrogeological cross-section showing the Beverley deposit (HR 1998a)

Table 1. Groundwater and mining solution quality at Beverley: Northen, Central and Southern ore zones, Northern field leach trial data (Injection and Extraction averages March to July 1998) and Retention Pond (July 1998; adapted from Mudd 2001a)

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

(mg/L)	Al	Fe	Mn	Si	SiO_2	U	^{226}Ra [a]	^{222}Rn [a]
Northern	0.2	0.7	0.2	48	ng	0.076	22-967	500-2,000
Central	ng	ng	ng	ng	ng	1.91	1.2-3,100	5-32,140
Southern	ng	ng	ng	ng	ng	0.70	13-111	20-585
Injection	91	109	0.7	138	294	2.9	8414	ng
Extraction	91	105	0.8	133	283	162	9881	ng
Ret. Pond	39	39	0.9	99	211	272	1713	ng

(μg/L)	B	Ba	Cd	Co	Cr	Cu	Ni	Pb	Se	V
Northern	1,600	53	0.2	100	20	30	4	40	1	1
Injection	1,000	37	117	20,000	100	200	8,470	160	410	1,100
Ext'n	1,100	39	116	20,000	580	200	8,330	790	410	1,130
R Pond	3,400	76	49	6,600	260	180	2,480	70	310	780

[a] ^{226}Ra and ^{222}Rn in Bq/L. Note: ng - not given; no redox data available.

The impact of unsealed exploration bores (when Beverley was planned as an open pit mine in the early 1970s), which increases the risk of excursions, has been recognised (Hancock 1986, 1988) although downplayed in more recent times.

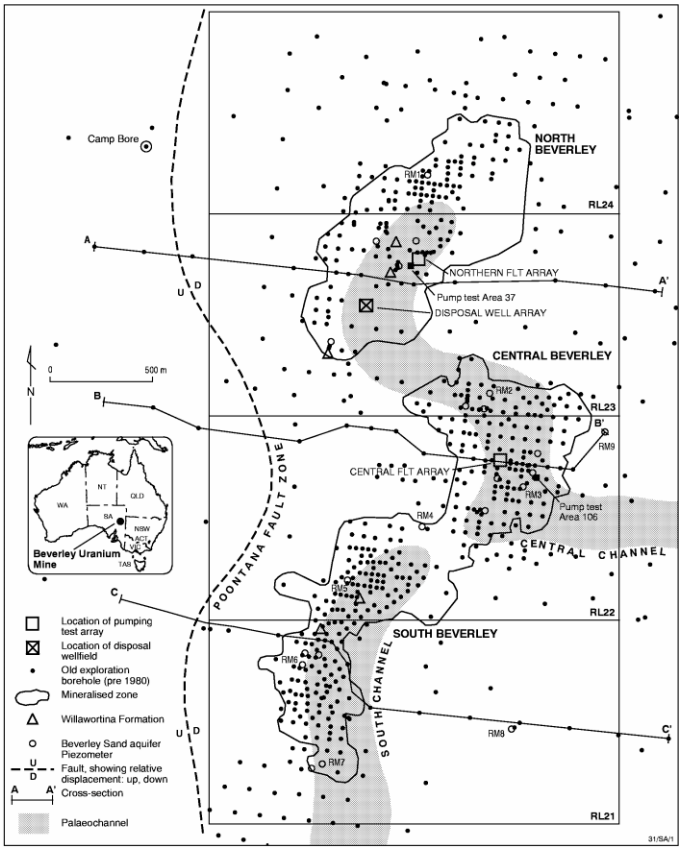

Fig. 3. Plan view of the ore zones and exploration bores at Beverley (Habermehl 1999).

Hydrogeological Impacts

After operating a trial acid leach mine during 1998 (producing 33.27 t U_3O_8) and releasing their environmental impact statement, further reviews were conducted to assess the hydrogeological impacts, centred on water quality and the 'semi-isolated' nature of the aquifers. Regulatory approvals were given in April 1999, making Beverley the western world's first acid leach uranium mine (OECD 2000).

In contrast to Beverley, commercial leach mines in the USA all use alkaline chemistry, generally dispose of liquid wastes through evaporation (or very deep groundwater injection) and are required to restore all impacted groundwaters to their pre-mining quality and state (Mudd, 1998, 2001a). As allowed, Beverley uses acid chemistry, disposes of liquid wastes by injection to the ore-zone and is not required to restore impacted groundwater. The basis for the approvals was that following mining the pH, metals and radionuclides will return to pre-mining conditions given several years, although no mechanisms or data were provided.

The Beverley aquifers were believed to be effectively isolated, posing minimal risk to surrounding groundwater if the above argument proved wrong.

The ore zone 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 neutralise the residual acid from migrating mining solutions and therefore precipitate gypsum. Due to the minimal degree of exploration data beyond the confines of the ore zones, however, this remains an untested hypothesis and no data has been released to demonstrate this mechanism could perform satisfactorily at Beverley. There is no redox data in public documents, thus precluding an accurate geochemical assessment of possible attenuation rates or reactions (Mudd 2001a).

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 Table 1). In the USA, gypsum formation was shown to be related to elevated salinity and radium in post-restoration groundwater (Mudd 2001a).

Honeymoon, South Australia

The Honeymoon project operated the first pilot solution mine in Australia during 1982 but failed to be developed after the withdrawal of government support in 1983. After a hiatus until the late 1990's, new owners Southern Cross Resources of Canada operated the old pilot mine again from 1998-2000 and received approvals for a commercial project by November 2001. Construction is set to start during 2002 with commercial operation expected by early 2003. The development history is given by Minad (1980, 1981), Mudd (1998, 2001a) and SCR (2000a, b).

Geology and Hydrogeology

The geology and hydrogeology of the Honeymoon and East Kalkaroo uranium deposits is described by Brunt (1978), Minad (1980, 1981), Curtis et al. (1990), SCR (2000a, b) and Mudd (1998, 2001a).

The Honeymoon and East Kalkaroo uranium deposits are located within the Yarramba palaeochannel in the southern Frome Embayment. The channel sands consist of three distinct layers which form the Basal, Middle and Upper aquifers. The Upper aquifer is occasionally used by pastoralists in the region while the Basal sand contains the Honeymoon deposit. Traces of uranium 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. Hydrogeological cross-sections are shown in Fig. 4, with a geological map shown in Fig. 5. Groundwater quality data is given in Table 2. The Honeymoon/East Kalkaroo deposits have several unique features related to the use of ISL, including pyrite at 5-15% compared to less than 2% in most USA deposits; higher salinity; low organic content (0.3%); and direct hydraulic connections between the palaeochannel aquifers due to gaps in the clay layers (Mudd 2001a).

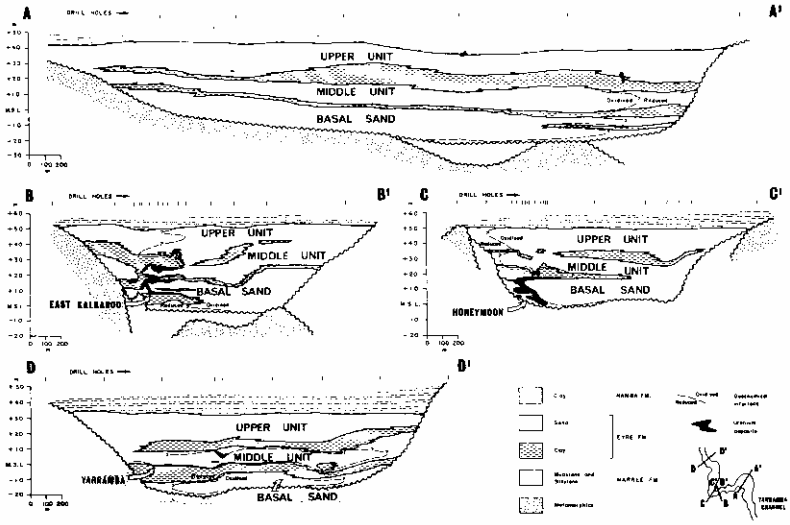

Fig. 4. Hydrogeological cross-sections of the Yarramba palaeochannel showing the Honeymoon, East Kalkaroo and Yarramba uranium deposits (Brunt 1978)

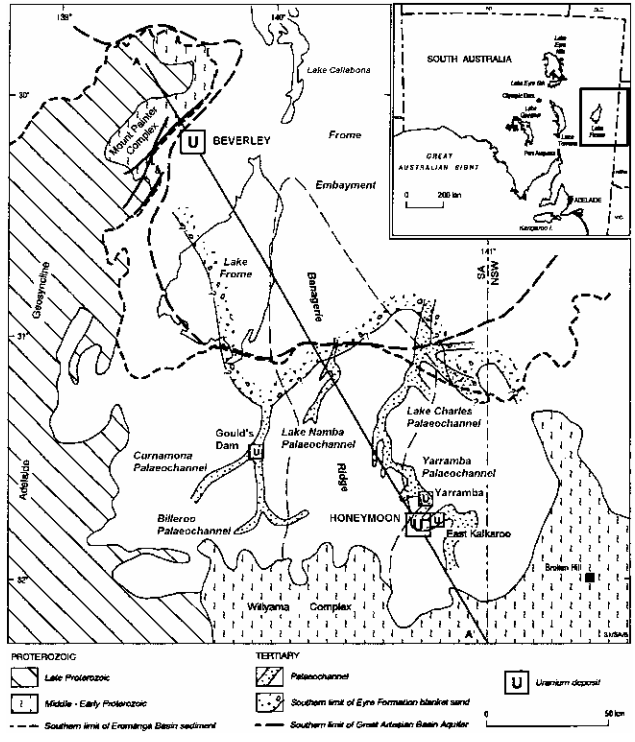

Fig. 5. Regional geological map of the Frome Embayment (adapted from Habermehl 2000)

Table 2. Average groundwater and mining solution quality at Honeymoon: Upper, Middle and Basal sands, mining solutions and liquid wastes (adapted from Mudd 2001a)

Units	pH -	TDS g/L	SO_4 g/L	Cl g/L	F mg/L	Na g/L	K mg/L	Ca mg/L	Mg mg/L
Upper	7.5	10.3	1.45	4.80	0.8	2.81	ng	478	260
Middle	7.0	11.4	1.54	5.37	0.5	3.39	ng	560	270
Basal	6.9	16.1	1.75	7.85	0.5	4.31	20.7	906	390
Leaching	2.2	16.43	5.30	8.47	0.6	6.17	ng	940	210
Wastes	2.3	19.8	6.11	8.02	1.9	5.60	27.5	1,000	430

(mg/L)	Org. C [a]	HCO_3	Al	Fe	SiO_2	U_3O_8	^{226}Ra [b]	^{222}Rn [b]
Upper	ng	187	<1.0	1.0	6.5	0.022	3.1	23
Middle	ng	160	<1.0	1.0	6.4	0.018	7	7
Basal	1.2	145	<1.0	1.0	7.6	1.2	205	5,000
Leaching	2	<5	15	260	ng	75	830	12,700
Wastes	ng	<5	28.3	200	101	2.3	405	ng

(µg/L)	Co	Cr	Cu	Mo	Ni	^{210}Pb [b]	Se	V	Zn
Upper	ng	ng	8	9	ng	3.6	14	<20	200
Middle	ng	ng	30	10	ng	6.6	19	<20	200
Basal	60	20	20	13	78	0.8	30	<20	190
Leaching	Ng	ng	7,000	3	ng	ng	55	4,000	110,000
Wastes	2,200	100	1,800	7.4	3,530	560	79	1,100	56,300

[a] Org. C - organic carbon. Note: ng - not given. [b] ^{226}Ra, ^{222}Rn and ^{210}Pb in Bq/L.

The 1982 trial encountered significant operational difficulties due to the precipitation of jarosite (Mudd 1998, 2001a). The 1998-2000 trial had an excursion in late 1999 where leach solutions were thought to have migrated through the lower clay confining unit (SCR 2001), despite assurances of minimal risk of excursions (eg. SCR 2000a, b). The excursion was controlled through remedial action, (ie. additional pumping), although it highlighted inadequacies with monitoring bores.

The only redox data available on the public record is from an analysis of mining solutions using different oxidising agents during the 1998-2000 trial (SCR, 2001). The use of oxygen, hydrogen peroxide, ferric sulfate and sodium chlorate gave redox potential values in leaching solutions of 415, 650, 684 and 970 mV, respectively, with the pregnant (recovered mining) solution being about 415 mV.

The approvals for Beverley set important precedents for acid leach mining in Australia that have major implications for the Honeymoon project (Mudd 2001a): 1) the project proposes to re-inject all liquid wastes into the Lower palaeochannel aquifer which is known to be hydraulically connected to the Upper aquifer occasionally used by pastoralists; 2) the potential for 'natural attenuation' is uncertain, although this depends on the reactivity of pyrite (or other reducing agents) 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).

Geochemical modelling of the interactions of Honeymoon mining solutions and liquid wastes with groundwater quality was presented by Pirlo (2000, 2001). 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, being calculated by 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. As with SCR (2000a, b), there is no data or analysis presented to justify the high dilution ratio of 10:1 (groundwater:mining solutions) used in mixing and geochemical modelling.

No published field evidence from the pilot leach trial corroborates the analysis by Pirlo (2000, 2001), especially concerning the redox state in the aquifers, nor does it demonstrate that natural attenuation has or will work at Honeymoon.

Manyingee, Western Australia

The Manyingee uranium deposit, discovered in 1974, was the site of pilot-scale alkaline leach mining in 1985. No more work has been undertaken at the site and it is currently owned by Australian explorer Paladin Resources Ltd.

The geology and hydrogeology of Manyingee is described by Valsardieu et al. (1981). The palaeochannel is buried beneath approximately 70 m of Cainozoic and Cretaceous sediments. Uranium mineralisation is generally found within the lower part of the Lower Cretaceous Birdrong sandstone, ranging from 70 to 110 m in depth, controlled by redox state and geologic structure. The sandstone units often contain abundant carbonaceous matter, including lignitic and wood fragments, as well as pyrite. The groundwater is of moderately low salinity of 3.4 g/L, being mainly Na and Cl with minor Mg, HCO_3 and SO_4.

The environmental and hydrogeological data from the 40.5 ML alkaline trial mine, as with Honeymoon and Beverley, has not been publicly reported (Mudd, 1998). The site did apparently undertake some groundwater restoration activities, although the extent or success of this work is unknown.

Discussion & Conclusions

The key for driving natural attenuation is for active reducing agents to be present, primarily organic carbon or sulfide (Buma 1979). In contrast, Riding et al. (1979) state that many roll-front uranium deposits in the Colorado Plateau of the USA showed poor correlation between reducing agents and uranium ores.

Both Honeymoon and Beverley contain low organic matter, with Honeymoon containing abundant pyrite. It would seem reasonable that the organic matter may have been consumed during formation of the respective roll-fronts and uranium precipitation. It is the organic matter remaining after acid leach mining, however, and the impacts of acidic, oxidised liquid wastes on aquifer sediments which will mainly determine if reducing conditions will re-establish after mining.

Morris (1984) stated that “reliance on this process [natural attenuation] has never been tested”. The time period and the rates at which natural processes could attenuate such levels of pollution are yet to be firmly established (Rojas 1987).

During operations, there is potential for excursions due to unsealed exploration bores, as well as excursions due to well casing failures (Marlowe 1984). Curiously, approvals for Beverley included provisions that liquid waste reinjection only occur in the Northern zone – the area of least exploration drilling and best quality groundwater (TDS ~3-6 g/L). This salinity is similar to regional pastoral use (excluding radionuclides), although often mines in Western Australia use saline groundwater up to 240 g/L (Sparrow & Woodcock 1993).

The use of acid in the USA was considered problematic due to restoration difficulties and higher salinity and some radionuclides in post-restoration groundwaters (related to gypsum formation during mining; Mudd 2001a). Pilot mines are used as the public basis for assessing commercial mines, and as such, acid leach mines have never been approved in the USA (Mudd 1998, 2001a).

Given the complexity of the geochemistry of in situ leach mines, it should be expected that detailed hydrogeological and geochemical studies be done for each proposed project. In Australia, the results from all leach mine trials at Beverley, Honeymoon and Manyingee have never been fully published and thus information is limited on their short and long-term impacts. Critically, the issues of geochemical conditions in the groundwater following mining have not been satisfactorily addressed, with no clear field evidence of natural attenuation at any site.

The standards 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, 2001a, b). This suggests that natural attenuation appears spurious at worst, ineffective at best.

Australia has the lowest continental rainfall with water a limiting and highly valuable environmental resource (Smith, 1998). The standards applied at the Australian acid leach uranium mine sites are not considered an acceptable approach for arid regions that are almost entirely dependent on groundwater.

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