Environmental Studies for the Four Mile Project

CONCEPTUAL HYDROGEOLOGICAL MODEL OF THE FOUR MILE REGION

- Version 3
- 20 November 2008
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Executive Summary

ES.1 Introduction

Quasar Resources Pty Ltd (Quasar), an affiliate of Heathgate Resources Pty Ltd, intends to develop the Four Mile uranium deposit, located approximately 8 km west north west of Heathgate’s Beverley Uranium Mine in South Australia’s north east (Figure ES1). The Four Mile Region lies between the Northern Flinders Ranges and Lake Frome, within the western part of the Frome Embayment.

Sinclair Knight Merz Pty Limited has been engaged by Quasar to conduct a review of the hydrogeological aspects of the broader Four Mile region to assist Quasar in obtaining environmental approvals for a mining lease at the Four Mile deposit.

This report aims to update previous hydrogeological studies of the region, undertaken to aid in environmental approvals for and mining at the Beverley Mine, with more recent and detailed information, sourced from both the vicinity of the Four Mile deposit and the broader Four Mile Region.

ES.2 Geological and Hydrogeological setting

ES.2.1 Geology

The Four Mile Embayment hosts the Four Mile deposit within Eyre Formation sediments, and within the Embayment the Eyre Formation aquifer is bounded to the east by the Poontana Inlier. Some remnant Eromanga Basin sediments may be present west of the Poontana Fault system. However, these sediments have been uplifted by basement tectonic movement within the Four Mile Embayment, and largely reworked during the Tertiary, to form the Eyre Formation sediments. East of the Poontana Fault system, intact Eromanga Basin sediments are present beneath the Beverley deposit and they deeper further to the east.

The geological setting of the Four Mile region can be divided into three main groups (Mt Painter Complex, Eromanga Basin, and Lake Eyre Basin), distinguished according to the relative age of the deposits.

Mt Painter Complex rocks of the Northern Flinders Ranges consist of granites and sequences of strongly folded crystalline metasedimentary rocks, deposited in the Proterozoic. The Complex is extensively faulted and fractured.
The sediments of the Eromanga Basin in the Four Mile region comprise of two distinct formations; the basal Cadna-owie Formation, and the overlying Bulldog Shale. The Cadna-Owie Formation is a thin, mainly fine grained sedimentary unit that extends throughout the Eromanga Basin, and consists of a pale grey siltstone to a fine grained sandstone, with locally developed medium to coarse grained sandstone interbeds. The Bulldog Shale overlies the Cadna-owie Formation and consists of a dark grey marine shaley mudstone, and in the study area is typically 50 to 150 m thick.

The Lake Eyre Basin sediments in the Four Mile area are comprised of the Eyre and overlying Namba Formations. The Eyre Formation (host of the Four Mile deposit) is widespread throughout the Lake Eyre Basin and commonly consists of a mature, carbonaceous, pyritic sand. The Namba Formation disconformably overlies Eyre Formation sediments and consists dominantly of olive-grey clay, silt and mudstone.

**ES.2.2 Hydrostratigraphy**

In the Four Mile region, there are five important hydrostratigraphic units (aquifers):

- the Willawortina Formation water table aquifer;
- the Namba Formation (Beverley) aquifer;
- the Eyre Formation (Four Mile) aquifer;
- the Cadna-owie (GAB) aquifer; and
- the Mt Painter Complex (fractured rock) aquifer.

The Namba Formation in the Beverley area contains mudstone units, both above and below the Beverley aquifer, which form confining aquitards that limit the transfer of groundwater between the Willawortina, Namba and Eyre Formation aquifers. Aquifer testing data collected by Heathgate indicates the Beverley aquifer within the Namba Formation is a completely closed system.

Drillhole data supported by field geophysical data indicate that Mt Painter Complex rocks are uplifted between the Four Mile and Beverly deposits to form an inlier (the Poontana Inlier) that is bounded by the Wooltana and Poontana Faults. The inlier forms the eastern bounding structure of an embayment (the Four Mile Embayment) within which the Four Mile deposit is located. Within the embayment, drilling data indicate that the Eyre Formation forms the main aquifer unit and overlies basement rocks. The Namba Formation is of limited saturation and the Willawortina Formation is unsaturated within the Embayment.
East of the Poontana Inlier, the Namba and Willawortina Formations are both saturated to some extent. The Namba and Eyre Formations thicken towards Lake Frome and overlie Eromanga Basin sediments.

**ES.2.4 Groundwater dynamics**

Groundwater elevation data for all aquifers in the Four Mile region (with the exception of the Eyre Formation within the Four Mile embayment) suggests a general west to east flow gradient, with recharge occurring via fractured rocks of the Northern Flinders Ranges, with a minor component of surface infiltration to shallow aquifers on the plains, and discharge occurring in the vicinity of Lake Frome. The groundwater elevation data for the Eyre Formation within the Four Mile Embayment suggests that the Poontana Inlier structure “channels” groundwater in a north easterly direction within the embayment, from where it then “spills” out of the northern end of the Embayment to the broader Eyre Formation aquifer.

Groundwater elevation data for the Four Mile Region suggests that a significant gradient exists between the fractured rock and sedimentary aquifers, to facilitate groundwater flow from the low permeability fractured rock aquifers in the west to the sedimentary aquifers of the Lake Frome Basin. Additionally, a significant upwards gradient exists east of the Poontana Inlier from the GAB aquifer to the overlying aquifers to make it very unlikely for “contamination” of the GAB aquifer to occur from the overlying formations.

**ES.2.5 Hydrogeochemistry**

Hydrogeochemical data for groundwaters in the Four mile Region show that several of the groundwaters within the region (Eyre, Namba and Willawortina Formations) demonstrate similar major ion compositions, with some variability between the formations.

Groundwaters from the fractured rock aquifer display no significant major ion domination across the Four Mile Region, however one sample suggests that, in the immediate Four Mile area, the fractured rock aquifer has a very similar chemical composition to the Eyre Formation.

The GAB aquifer groundwaters are significantly different to those of the Eyre, Namba and Willawortina Formations indicating there is very little interaction, if any, with these upper units. Additionally, the anionic composition of the GAB aquifer groundwaters becomes dominated by bicarbonate rather than chloride to the east of Lake Frome, suggesting separate groundwater types within this aquifer on either side of Lake Frome.
The hydrogeochemistry of groundwater and surface waters in the vicinity of Lake Frome supports the notion that the Lake forms a regional discharge sink for the Willawortina and Eyre Formation aquifers. In addition, discharging groundwaters from the GAB “mound” springs found on the eastern shore of the Lake are shown to comprise greater than 90% GAB aquifer groundwater, with only a very minor component of spring discharge water sourced from the Willawortina or Eyre Formations due to mixing with brines beneath the Lake. This groundwater discharge zone forms an effective groundwater divide between the Four Mile Region groundwater system and the GAB proper (i.e. to the east and north of Lake Frome).

**ES.3 Conceptual hydrogeological model**

Figure ES2 presents a schematic of the conceptual hydrogeological model of the Four Mile Region.

On a regional scale, groundwater recharge occurs in the west via the fractured rock aquifer where it outcrops as the Northern Flinders Ranges, and largely via creek washouts and lines on the ‘plains’ of the Frome Embayment. The fractured rock basement aquifers discharge to the sedimentary aquifers of the Frome Embayment and terminal discharge for the groundwater system occurs largely via evaporative processes occurring where groundwater lies close to the surface, predominantly near and within Lake Frome and Lake Callabonna to the east.

In the vicinity of the Four Mile deposit, water level data for the Eyre and Namba Formations suggest that the Poontana Inlier forms a north-south trending bounding structure to the east of the Four Mile embayment and directs groundwater flow northwards within the embayment. The Poontana Inlier structure is confirmed by both drilling and geophysical data.

The (west of Lakes Frome and Callabonna) GAB aquifer is found east of the Poontana Inlier and lies beneath the Bulldog Shale aquitard at significant depth in relation to the Eyre, Namba and Willawortina Formations. The available hydrogeochemical dataset strongly supports the notion that the GAB aquifer is hydraulically separate from the younger overlying formations, including the aquifers which host the Four Mile and Beverley deposits. This is supported by aquifer pressure data.

The available hydrogeochemical dataset also shows that the GAB aquifer east and west of Lakes Frome and Callabonna has two different chemical signatures, with the Lakes forming a divide between the broader GAB aquifer groundwaters that are recharged along the Great Dividing Range, and those GAB groundwaters west of Lake Frome (in the closer Four Mile
Region). This is supported by potentiometric data which shows a potentiometric depression within the GAB aquifer in the vicinity of the eastern shores of Lake Frome and Lake Callabonna, likely as a result of upwards discharge from the GAB aquifer via conductive faults to “mound” springs found on the surface of Lake Frome, but also due to upward leakage into shallower sediments.
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1. Introduction

1.1. Background

Quasar Resources Pty Ltd (Quasar), an affiliate of Heathgate Resources Pty Ltd (Heathgate), intends to develop the Four Mile uranium deposit (Four Mile), located approximately 8 km west north west of Heathgate’s Beverley Uranium Mine in South Australia’s north east (Figure 1.1). The Four Mile Region lies between the Northern Flinders Ranges and Lake Frome, within the western part of the Frome Embayment.

Sinclair Knight Merz Pty Limited (SKM) has been engaged by Quasar to conduct a review of the hydrogeological aspects of the broader Four Mile region to assist Quasar in obtaining environmental approvals for a mining lease at the Four Mile deposit.

1.2. This Report

Prior to Quasar commencing investigations into the Four Mile deposit, hydrogeological studies in the region have concentrated on Heathgate’s Beverley deposit, to aid in environmental approvals for, and mining at, the Beverley Mine.

Whilst a large part of the regional geological and hydrogeological discussion in the documents prepared for the Beverley Mine remains valid for the Four Mile study area, this report aims to update these studies with more recent and detailed information sourced from both the vicinity of the Four Mile deposit and the broader Four Mile Region.
2. Geological Setting

2.1. Overview

The geological setting of the Four Mile region can be divided into three main groups, distinguished according to the relative age of the deposits.

The oldest of the groups is the Proterozoic aged rocks of the Mt Painter Complex, which are in part uplifted to form the Northern Flinders Ranges. To the east of the ranges, in what is known as the Frome Embayment, the basement rocks are overlain by the Mesozoic aged Eromanga Basin, one of three sub-basins which form the Great Artesian Basin. Overlying the Eromanga Basin sediments are the sediments of the Tertiary aged Lake Eyre Basin.

Quaternary sediments of the Willaworta Formation overly the Lake Eyre Basin sediments and consist of material derived from weathering of the Mount Painter Complex rocks where they outcrop as part of the Northern Flinders Ranges.

The Four Mile Embayment hosts the Four Mile deposit within Eyre Formation sediments, and within the Embayment the Eyre Formation aquifer is bounded to the east by the Poontana Inlier. Some remnant Eromanga Basin sediments may be present west of the Poontana Fault system. However, these sediments have been uplifted by basement tectonic movement within the Four Mile Embayment, and largely reworked during the Tertiary, to form the Eyre Formation sediments. East of the Poontana Fault system, intact Eromanga Basin sediments are present beneath the Beverley deposit and they deeper further to the east.

Table 2.1 presents a summary of the geological units in the Four Mile region and Figure 2.1 presents a geological locality plan.

2.2. Mt Painter Complex

Mt Painter Complex rocks of the Northern Flinders Ranges consist of a predominantly arenaceous sequence of strongly folded crystalline metasedimentary rocks, deposited in the Proterozoic (Coats and Blissett, 1971). Intrusive granites are present in the core of the Mt Painter Complex. The Complex is extensively faulted and fractured. Further west lie Adelaide Geosyncline rocks which comprise the majority of the Flinders Ranges.
### Table 2.1 Summary of stratigraphic units (Flow, 2007)

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<th>Time Unit</th>
<th>Map Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
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<tr>
<td>Quaternary</td>
<td>Qha1</td>
<td>Sands and Gravels</td>
<td>Modern stream deposits. Intermittantly reworked sands, gravels and cobbles.</td>
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<tr>
<td></td>
<td>Qhe2</td>
<td>Simpson Sand</td>
<td>Modern dune system of Stzelecki Desert.</td>
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<tr>
<td>Cainozoic</td>
<td>Qec</td>
<td>Coonarbine Formation</td>
<td>Flat low-lying clayey sand plains.</td>
</tr>
<tr>
<td>Late Pleistocene to Holocene</td>
<td>Qpa</td>
<td>Euriinilla Formation</td>
<td>Flat low-lying clayey sand plains with lower part cemented by gypcrete or calcrite</td>
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<tr>
<td>Medial to Late Pleistocene</td>
<td>Qec</td>
<td>Coonarbine Formation</td>
<td>Flat low-lying clayey sand plains.</td>
</tr>
<tr>
<td>Tertiary</td>
<td>TpQaw</td>
<td>Willawortina Formation</td>
<td>Sheeted gravels and clayey sands. Forms basic landscape of uplifted High Plain flanking the Flinders Ranges.</td>
</tr>
<tr>
<td>Late Eocene to Palaeocene</td>
<td>Tsi</td>
<td>Undifferentiated Duricrusts</td>
<td>Silcrete-Percellanite-Greybilly, usually local cap rocks to other units in proximity to the Range Front. Multiple ages.</td>
</tr>
<tr>
<td>Miocene</td>
<td>Topn</td>
<td>Upper Namba Formation</td>
<td>Olive-grey swelling clay, dolomite nodules and beds, greenish laminated silt and fine sands. Includes Beverley Sands.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower Namba Formation</td>
<td>Olive-grey swelling clay, dolomite nodules and beds, greenish laminated silt and fine sands. Localised dark sandy claystones.</td>
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<tr>
<td>Palaeocene to Eocene</td>
<td>Taee</td>
<td>Eyre Formation</td>
<td>Uncemented quartz sand, some clay beds, minor lignite. Often capped by Tsi. Exposed near ranges 25 km north of Beverley. Includes Four Mile Sands.</td>
</tr>
<tr>
<td>Mesozoic</td>
<td>Kmb</td>
<td>Bulldog Shale</td>
<td>Clay and silt. Local exposures in the western portion of the High Plains. Concealed at depth in the east.</td>
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<tr>
<td>Cretaceous</td>
<td>Knc</td>
<td>Cadna-Owie Formation</td>
<td>Quartz sandstone, pebbly conglomerates and basal channel fill deposits. Local relict outliers in the ranges and low relief areas of the western portion of the High Plains.</td>
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<td>Palaeozoic</td>
<td>eOdi</td>
<td>British Empire Granite</td>
<td>Granite, Freeling Heights area.</td>
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<tr>
<td>Neoproterozoic</td>
<td>Pn</td>
<td>Adelaide Geosyncline Units</td>
<td>Sandstones, siltstones, shales and limestones, lesser mafic volcanics.</td>
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<tr>
<td>Meso / Palaeo-Proterozoic</td>
<td>Pmp</td>
<td>Mt Painter Complex Units</td>
<td>Granites, quartzite, pebble conglomerates, schists and gneiss.</td>
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FIGURE 2.1

SURFICIAL GEOLOGY

Localities
- Beverley Camp
- Beverley Processing Plant
- Old Paralana
- East Painter Camp
- Pepegoona Hut
- North Mulga

Surface Water Features
- Spring
- GAB Spring

Interpreted Faults

Surface Geology (PIRSA)
- Willawarta Formation and modern equivalents
- Eromanga Basin sediments
- Proterozoic meta-sediments
- Proterozoic intrusives and extrusives

Four Mile Mine Lease Application

Four Mile Region Conceptual Hydrogeological Model

SKM
2.3. Eromanga Basin

The sediments of the Eromanga Basin in the Four Mile region comprise of two distinct formations; the basal Cadna-owie Formation, and the overlying Bulldog Shale.

The Cadna-Owie Formation is a thin, mainly fine grained unit that extends throughout the Eromanga Basin (Kreig and Rogers, 1995). The formation represents a transition from terrestrial-freshwater to marine conditions and consists of a pale grey siltstone to a fine grained sandstone, with locally developed medium to coarse grained sandstone interbeds.

The Bulldog Shale is a dark grey marine shaley mudstone, having common fossil assemblages (Kreig and Rogers, 1995). Its maximum known thickness can range greater than 300 m, however in the study area is typically 50 to 150 m thick. The unit is known to contain thin sandstone beds which are often mis-interpreted on a broad scale as the younger Coorikiana Sandstone found elsewhere in the Eromanga Basin.

Eromanga Basin sediments are interpreted to be present in the immediate Four Mile area in historical geological mapping work (refer Figure 2.1). Palynological analysis of rock samples obtained during drilling investigations indicate that the sandstone hosting mineralisation in the Four Mile East orebody comprises reworked Cretaceous sediments, which were transported in the Tertiary, to form the Eyre Formation sediments (refer Section 2.4). Further towards the south west of the Four Mile Embayment in the vicinity of the Four Mile West orebody, where basement rocks are elevated against the range front, palynological data indicate that some intact Cretaceous sandstones may be present.

2.4. Lake Eyre Basin

The Lake Eyre Basin sediments in the Four Mile area are comprised of the Eyre and overlying Namba Formations.

The Eyre Formation (host of the Four Mile deposit) is widespread throughout the Lake Eyre Basin (Callen et al, 1995). The Eyre Formation commonly consists of a mature, carbonaceous, pyritic sand, with grain size varying from silt to gravel. The deposition environment of the Eyre Formation is believed to be one of braided streams originating in the uplifted Olary, Barrier and Northern Flinders Ranges flowing into the subsided Lake Eyre Basin.

The Namba Formation disconformably overlies Eyre Formation sediments and consists dominantly of olive-grey clay, silt and mudstone. The unit hosts some discontinuous, bounded sand horizons as identified at the Beverley deposit, within what are interpreted to be palaeochannel sand (stringer) deposits. On a regional scale, in the Four Mile Embayment and Beverley Mine area, low overall
permeability of the Namba Formation means that it serves more as an aquitard rather than an aquifer.
3. Hydrogeological Setting

3.1. Hydrostratigraphy

3.1.1. General

In the Four Mile region, there are five important hydrostratigraphic units (aquifers):

- the Willawortina Formation water table aquifer;
- the Namba Formation (Beverley) aquifer;
- the Eyre Formation (Four Mile) aquifer;
- the Cadna-owie (GAB) aquifer; and
- the Mt Painter Complex (fractured rock ) aquifer.

The Namba Formation in the Beverley area contains mudstone units, both above and below the Beverley aquifer, which form confining aquitards that limit the transfer of groundwater between the Willawortina, Namba and Eyre Formation aquifers. Similarly, the Bulldog Shale aquitard underlying the Eyre Formation provides a confining layer for the Cadna-owie Formation aquifer. Aquifer testing data collected by Heathgate indicates the Beverley aquifer within the Namba Formation is a completely closed system in all directions.

3.1.2. Cross sectional profiles

Drillhole data collected by Quasar and Heathgate during investigations both at the Beverley and Four Mile Deposits show that the relationships between the geological units in the Four Mile region are complex, with extensive faulting associated with Flinders Ranges uplift tectonic events, significantly displacing the units vertically. This vertical displacement and subsequent erosion has resulted in older geological units (Eyre Formation and Proterozoic basement rocks) beneath the Four Mile deposit lying at similar elevations to younger units (Namba Formation) further to the east.

Cross sectional profiles for the Four Mile region, developed from Quasar and Heathgate drillhole data coupled with regional drillhole data sourced from the South Australian Resources Information Geoserver (SARIG), are presented on Figures 3.2 – 3.6. Figure 3.1 shows the locations of these cross sections, and also shows the location of drillholes from which the stratigraphic interpretation have been drawn. Fault locations are taken from SARIG and the degree of fault offset shown in the cross sections is approximate only.
FIGURE 3.2
GEOLOGICAL PROFILE 1

Four Mile Deposit
Beverly Deposit
Lake Callabonna
Royston Inlet

Cenozoic
- Willawartina Formation
- Nymba Formation
- Eyre Formation

Mesozoic
- Bulldog Shale
- Cadina-owie Formation

Basement Formation
FIGURE 3.4
GEOLOGICAL PROFILE 3
FIGURE 3.6
GEOLOGICAL PROFILE 5

Willaworta Formation
Namba Formation
Byre Formation
Bulldog Shale
Cadne-owie Formation
Basement Formation
Stratigraphic interpretation of drill hole data was undertaken by Quasar and Heathgate geologists. The interpretation of stratigraphic units was based on inspection of geological and geophysical logs of available drillholes. There is a reasonable degree of confidence in this interpretive work due to the considerable experience that Quasar and Heathgate have amassed regarding the geology in the Four Mile region, and the distinct geophysical markers between the main stratigraphic units that facilitate stratigraphic interpretation.

Profiles 1 and 2 (Figure 3.2 and 3.3) show that vertical displacement of sediments by the Poontana Fault system, east of the Northern Flinders Ranges, has uplifted basement rocks and the overlying Namba and Eyre Formations in the immediate vicinity of the fault system, so that an embayment (the “Four Mile Embayment”) is formed west of the fault system. The uplifted basement rocks form an inlier (the “Poontana Inlier”) between the Four Mile Embayment and the sediments of the Lake Frome and Eromanga Basins to the east.

Profile 3 (Figure 3.4) commences in the south of the Four Mile Embayment, and shows the Eyre Formation sediments dipping eastwards from the edge of the Northern Flinders Ranges towards the Poontana Fault. Insufficient drillhole data in the vicinity of the Poontana Inlier makes the eastern edge of the Four Mile Embayment difficult to define along this profile line, although it can be inferred by the large displacement of the Namba Formation approximately 12 km along the profile.

Data obtained through a surface gravity survey (Haines, 2005) is shown in Figure 3.7. The gravity data, which are inferred to be an indicator of depth to basement, shows that the elevated basement of the Poontana Inlier continues from east of the Four Mile deposit (where the elevated basement structure is confirmed by drilling) much further to the south.

Profile 4 (Figure 3.5) extends in a north easterly direction from the south of the immediate Four Mile area, running parallel to the Northern Flinders Ranges and the Poontana Inlier. The profile shows the onlap of Eromanga Basin sediments onto the steeply northwards dipping basement rocks. The Eyre and Namba Formation sediments thin and shallow towards the southern end of the Four Mile Embayment, coincident with the uplifted basement rocks. The presence of the Poontana Fault is again noted around 15 km along the profile.

Profile 5 (Figure 3.6) is a north-south trending cross section from the western side of Lake Frome to west of Lake Callabonna. This profile shows that away from the Northern Flinders Ranges, the geology of the Lake Eyre Basin is relatively uniform, with the Eyre Formation lying beneath around 110 m of Namba Formation.
Four Mile Region Conceptual Hydrogeological Model

FIGURE 3.8

SURFACE GRAVITY SURVEY

Digital Terrain Model
m AHD

High : 1432
Low : -26

Surface Water Feature
Track
Minor Road
Four Mile Mine Lease Application
Beverly Mine Lease
Interpreted Faults
GAB Spring
Spring

I:\VESA\Projects\VE2190\Technical\GIS\Mapping\Gravity.mxd
3.1.3. Structural elevation contour plots

Structural elevation (structural) contours for the top of the Namba Formation, Eyre Formation and basement rocks in the Four Mile area, compiled from Quasar and Heathgate drillhole data, are presented on Figures 3.8 to 3.10. The contour plots for the Namba and Eyre Formations (refer Figures 3.8 and 3.9) show clearly the bounding structure of the Poontana Inlier. The inlier itself is interpreted from the basement structural contour plan (refer Figure 3.10) as relatively steeply plunging elevations at the northeastern edge of the Four Mile Lease Application area.

3.2. Groundwater Dynamics

3.2.1. Overview

The Four Mile Region groundwater dynamics draws on groundwater level data collected by Quasar and Heathgate during investigations at the Beverley and Four Mile deposits, with additional data sourced from the South Australian Government’s Drillhole Enquiry System. The distribution of groundwater level data covers both the immediate area and host aquifer at the respective deposits. Broader scale groundwater dynamics of the Lake Frome Basin were investigated by Kerr (1965). This research is incorporated in the discussion below.

Aquifer pressure data for the Namba, Eyre and Beverley Mine GAB aquifers have been collected by Quasar and Heathgate. Water levels are measured in the field to an accuracy of 0.01 m. Reference elevations are calculated from a LiDAR ground surface survey (FUGRO, 2007), which has a pixel size of 2 m, and a precision of approximately 0.1 m. Aquifer pressure data can be considered accurate to within 0.2 m.

3.2.2. Willawortina Formation aquifer

Previous groundwater investigations at the Beverley Deposit (Flow, 2007) interpreted a north west to south east regional potentiometric gradient within the Willawortina Formation (Figure 3.11). This potentiometric gradient was derived from data presented in Kerr (1965). Groundwater quality data show that salinity within the Willawortina aquifer generally increases away from creeklines (Flow, 2007), suggesting that groundwater recharge along those creeklines plays an important role in the dynamics of the aquifer. The Willawortina Formation is unsaturated at the Four Mile deposit. Discharge from the Willawortina Formation aquifer is in the Lake Frome area, dominantly as evaporation from a shallow brine water table that resides below the lake bed (Draper and Jensen, 1974).
FIGURE 3.9
INTERPRETED EYRE FORMATION STRUCTURAL ELEVATION CONTOURS
POONTANA INLIER
Surface Water Feature
Track
Spring
GAB Spring
Four Mile Mine Lease Application
Beverly Mine Lease
Stratigraphic Drillholes (Eyre Fm)
Digital Terrain Model
m AHD
High: 1432
Low: -26

Four Mile Region Conceptual Hydrogeological Model

I:\VE3\Projects\VE23090\Technical\GIS\Mapping\Top Eyre.mxd
FIGURE 3.11
INTERPRETED WILLAWORTINA FORMATION
GROUNDWATER ELEVATION CONTOURS

Localities

- Four Mile Region Conceptual Hydrogeological Model
- Interpreted Faults
- Surface Water Feature
- Spring
- GAB Spring
- Interpreted Faults
- Localities

Interpreted groundwater flow direction

Four Mile Mine Lease Application
Beverly Mine Lease

Willawortina Fm RSWL (mAHD) (Row, 2007)

0 2.5 5 10 Kilometres

I:\ESA\Projects\E230.80\Technical\GIS\Mapping\Willawortina_Fm_RSWL.mxd
3.2.3. **Namba Formation (Beverley) aquifer**

West of the Poontana Inlier, within the Four Mile Embayment, the Namba Formation lies at relatively shallow depth and is for the most part unsaturated. However, east of the Poontana Inlier, groundwater elevation data in the vicinity of the Beverley deposit suggests an easterly trending pressure gradient (Figure 3.12). The vertical and lateral boundaries which confine the Beverley Aquifer and render it a stagnant system have been extensively tested and documented as part of the Beverley EIS and ongoing approvals (HGR, 1998, Lisdon, 1998). The observed slight pressure gradient is considered to be due to long term steady-state pressure equilibrium with the overlying Willawortina Formation.

3.2.4. **Eyre Formation (Four Mile) aquifer**

Groundwater elevation data for the Eyre Formation aquifer in the immediate Four Mile area (i.e. west of the Poontana Inlier) shows a south west to north east groundwater flow direction, consistent with the interpreted alignment of the Four Mile Embayment, and the Poontana Inlier and associated fault system (Figure 3.13). It appears that recharge to the Eyre Formation in this area occurs via the Northern Flinders Ranges to the immediate west and also via creeklines (such as Paralana Creek) south of the Four Mile deposit.

Aquifer recharge areas are evident in the southwest of the embayment where the Four Mile Creek and Paralana Creeks cross outcropping Eyre Formation sediments, and at these locations rapid infiltration would be expected during creek flows. These recharge areas show anomalously high levels of natural radioactivity associated with uranium species (Figure 3.14). Recharge to the Eyre Formation is also likely to occur via lateral and upward vertical leakage from the fractured rock aquifers.

Groundwater flow is ‘channelled’ northwards along the Four Mile Embayment by the bounding basement rocks of the Northern Flinders Ranges to the west and the Poontna Inlier to the east, before discharging where the Eyre Formation deepens at the northern end of the embayment (refer Figure 3.4) to enter the broader Eyre Formation outside of the Embayment. Discharge to the Namba Formation at this location is considered unlikely due to the absence of permeable units observed within the Namba Formation in drillholes in this area. Regionally, discharge from the Eyre Formation occurs in the Lake Frome area as evaporation from a shallow brine water table that resides below the lake bed (Draper and Jensen, 1974).
FIGURE 3.13

INTERPRETED EYRE FORMATION GROUNDWATER ELEVATION CONTOURS

POONTANA INLIER
FIGURE 3.14
REGIONAL RADIOMETRICS

Surface Water Feature
- Four Mile Mine Lease Application
- Beverly Mine Lease
- GAB Spring
- Interpreted Faults

Four Mile Region Conceptual Hydrogeological Model

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3.2.5. Eromanga Basin aquifer

Groundwater level data for the Eromanga Basin aquifer (the GAB aquifer) shows that a broad groundwater depression exists in the vicinity of the eastern shores of Lake Frome, with groundwater flow towards the saline lake systems from the west, north and east (Figure 3.15). The depression results in a head change of up to 40 m between the western margin of the Eromanga Basin aquifer beneath the Beverley deposit and the eastern shore of Lake Frome. The depression is likely driven by groundwater discharge from the GAB aquifer via the saline lake systems. GAB aquifer groundwater discharge in this area is likely via upward leakage and evaporation from the lake beds (both diffuse leakage and also fault related direct leakage) and via GAB ‘mound’ springs that are present on the surface of Lake Frome (Habermehl, 1980) (refer Figure 3.15).

At the Beverley deposit, the GAB aquifer has a pressure head around 75 m greater than the Namba Formation, suggesting no credible possibility of potential contamination of groundwater within the GAB aquifer that might arise as a result of mining operations at Beverley. Although the GAB aquifer is not found west of the Poontana Inlier beneath the Four Mile deposit, groundwater pressures in the GAB aquifer east of the inlier are, again, significantly greater (35 to 40 m) than those of the Eyre Formation, which hosts the Four Mile deposit west of the inlier.

The large measured separation in groundwater pressures between the GAB aquifer and the overlying Eyre and Namba Formations suggests that the fault structures of the Poontana Fault System are relatively impermeable, at least within the unconsolidated sediments of the Eromanga and Lake Eyre Basins.

Draper and Jensen (1974) report evidence that there has been a reduction in GAB pressure in the Lake Frome Embayment from the 1930s to 1970s due to wasteful pastoral use. Firstly, water levels in some mound springs were below ground surface in the 1974 field survey indicating the aquifer pressure that drove mound formation is no longer present. Secondly, local graziers reported a reduction in bore flows of some 25 to 50% over the preceding 30 to 40 years. It is possible that the observed depression in the potentiometric surface of the GAB aquifer at the south eastern extent of Lake Frome is caused by discharge from pastoral bores, just as much as it is caused by natural discharge processes via mound springs and upward leakage beneath Lake Frome.

3.2.6. Fractured Rock Aquifer

Groundwater level (pressure) data for the Fractured Rock aquifer of the Northern Flinders Ranges, sourced mainly from the DWLBC drillhole enquiry system, shows that aquifer pressure in this system ranges from approximately 60 to 550 m AHD (Figure 3.16). The relatively high groundwater pressures suggest the fractured rock system exhibits sufficient pressure to enable recharge into the sedimentary aquifers of the western Frome Embayment.
INTERTRETED FRACTURED ROCK
GROUNDWATER ELEVATION CONTOURS

Four Mile Region Conceptual Hydrogeological Model

FIGURE 3.16
3.3. Hydrogeochemistry

3.3.1. Overview

Groundwater from across the Four Mile Region has been sampled by Quasar and Heathgate from wells installed as part of investigations into both the Four Mile and Beverley deposits, as well as regional pastoral bores, with the samples submitted to NATA accredited laboratories for analysis under standard chain of custody procedures. This data set includes samples obtained during the Beverley EIS process, data collected during operation of the Beverley mine, and more current sampling of wells constructed in the Eyre Formation in the Four Mile Embayment and down gradient of the embayment within the Lake Frome Basin.

The following discussion involves interpretation of hydrogeochemical data provided by Quasar.

3.3.2. Piper Diagrams

Figure 3.17 presents a Piper (tri-linear) diagram that compares concentrations of cations and anions reported for different groundwater sample points across the Four Mile Region. Piper diagrams are useful in showing whether different groundwaters have similarities, suggesting interaction between the sampled groundwater, or dissimilarities, suggesting limited or no interaction between the sampled groundwater.

The Piper plot of the groundwater sample points across the Four Mile Region has been used to define the hydrogeochemical facies of each of the sampled aquifers, and of surface water sampled by Quasar and Heathgate throughout the Four Mile Region. Table 3.1 presents the composition types of groundwater from each of the formations, along with surface water.

Table 3.1 Composition of waters within the Four Mile region based on Piper Plot analysis

<table>
<thead>
<tr>
<th>Formation / Source</th>
<th>Water Composition (Type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyre Formation</td>
<td>Sodium potassium - chloride</td>
</tr>
<tr>
<td>Fractured Rock</td>
<td>Mixed cations – mixed anions</td>
</tr>
<tr>
<td>GAB Aquifer</td>
<td>Sodium potassium – bicarbonate (east of Lake Frome)</td>
</tr>
<tr>
<td></td>
<td>Sodium potassium – chloride (west of Lake Frome)</td>
</tr>
<tr>
<td>Namba Formation</td>
<td>Sodium potassium chloride sulfate</td>
</tr>
<tr>
<td>Willawortina Formation</td>
<td>Sodium potassium – mixed anion</td>
</tr>
<tr>
<td>Surface water</td>
<td>Sodium potassium – mixed anion</td>
</tr>
</tbody>
</table>

Piper Diagram of Four Mile Region Waters

Legend
- Eye Formation
- GAB
- Fractured
- Ramba Formation
- Surface Water
- Willowpoint Form

FIGURE 3.17

Four Mile Region Conceptual Hydrogeological Model

PIPER DIAGRAM

FIGURE 3.17
Several of the waters (Eyre Formation, Namba Formation, Willawortina Formation and surface water) display similar compositions. Groundwaters from both the Eyre Formation and the Namba Formation are relatively spatially compact in terms of sample spread, although the Namba Formation sample set contains a few outliers where the sulfate:chloride ratio is significantly increased (maximum of 33:1, monitoring well H41 located within the Beverley mine lease extension) over the data set average (1.7:1, n=50).

The Willawortina Formation sample spread is less compact than the Eyre or the Namba Formations, and generally comprises more calcium and magnesium, and more carbonate / bicarbonate. The Willawortina Formation dataset comprises more sampling locations over a significantly larger area than either of the Eyre or Namba Formations and, thus, there is more inherent variation in terms of groundwater composition as calcium becomes more dominant to the east. Furthermore, the Willawortina Formation flow system is driven by surface infiltration of water, and this localised variable recharge mechanism would be expected to produce sample variability.

Surface water samples display a general sodium potassium – mixed anion composition, although carbonate / bicarbonate is slightly more dominant than in groundwater samples, as would be expected in an “open” system (i.e. where water is in contact with atmospheric CO₂ and thus equilibrates to partial pressure of CO₂ in the atmosphere).

Groundwater samples from the Fractured Rock aquifer displayed a much more variable composition than any of the other waters within the Four Mile region, reflecting the large geographic spread of this data set and inherent variability of fractured rock aquifer recharge mechanisms, and the potentially variable host rock composition.

Groundwater from the GAB aquifer displays a different general composition to that of the other Four Mile Region groundwaters, as it has a sodium potassium - chloride composition west of Lake Frome (Camp Bore, Plant 1 and Plant 2), and a sodium potassium – bicarbonate composition east of Lake Frome (Cooterbarlow 1 and 3, and Moolwatana 2), with very little calcium, magnesium and sulfate in comparison to other waters in the Four Mile Region. Figure 3.18 presents a GAB aquifer sample point locality plan.

The Piper plot presented as Figure 3.17 demonstrates differing compositions between groundwaters of the GAB aquifer and those of the Eyre formation. This is further demonstrated in a revised Piper Plot shown in Figure 3.19, which focuses on the composition of the Eyre Formation and GAB aquifer groundwaters. The anionic composition of the Eyre Formation is dominated by chloride (approx. 60%- 80%) but includes sulfate (approx. 0% to 30%) and some bicarbonate (0%-20%). The anionic composition of the GAB groundwaters comprise very little sulfate (<10%) and increased proportions of carbonate/bicarbonate (>20%).
FIGURE 3.18
GAB AQUIFER HYDROGEOCHEMISTRY SAMPLE POINTS

- Lake Frome
- CAMP BORE
  - Plant GAB 2
  - Plant GAB 1
- Moolawatana Bore 2
- Cootabarlow Bore 3
- Cootabarlow Bore 1

Surface Water Feature
Spring
GAB Spring
Interpreted Faults
Minor Road
Four Mile Mine Lease Application
Beverly Mine Lease

GAB AQUIFER HYDROGEOCHEMISTRY SAMPLE POINTS

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FIGURE 3.19

GAB AQUIFER AND EYRE FORMATION PIPER DIAGRAM
3.3.3. **Stiff Diagrams**

Analysis of the averaged concentrations of major cations and anions from both the GAB aquifer and the Eyre Formation using a Stiff Plot (Figure 3.20) indicates that the groundwaters are dominated by (and have relatively similar concentrations of) sodium and potassium, however the Eyre Formation groundwaters contain more calcium, magnesium and sulfate. Additionally, the Eyre Formation groundwaters demonstrate a similar polygon to the fractured rock aquifer beneath the Four Mile deposit (refer Figure 3.20), supporting the concept of discharge from the fractured rock into the Eyre Formation, although to date there is only a single fractured rock groundwater analysis beneath the Eyre Formation in the vicinity of the Four Mile deposit.

The GAB aquifer groundwater demonstrates two main anion groups (refer Figure 3.20), with the wells located west of Lake Frome being dominated by chloride, and the wells located to the east of Lake Frome being dominated by carbonate / bicarbonate. The Eyre Formation groundwaters differ slightly in composition across the sample set. Most of the samples demonstrate a similar polygon when plotted on Stiff Plots (Figure 3.21) with the exception of one well which is located to the east of the Poontana Inlier (4MRMW15) which shows an increased concentration of magnesium and sulfate.

3.3.4. **Bicarbonate Ratio Scatter Plot**

A scatter plot of the HCO₃/Cl ratio vs Cl for all available groundwater sample points in the Four Mile Region is presented on Figure 3.22. The plot shows the typical evolution of groundwaters along their respective flow paths, from high to low HCO₃/Cl ratios. The fractured rock groundwaters, as well as some Willawortina Formation groundwaters, have high HCO₃/Cl ratios, indicating that those groundwaters are close to recharge points.

The groundwater sample from the 4M0012 well, which is installed into the fractured rock aquifer beneath the Four Mile deposit, plots further up the flow path than most Eyre Formation data points (refer Figure 3.22). This supports the concept that groundwater discharges from the fractured rock aquifer to the Eyre Formation aquifer.

3.3.5. **Lake Frome**

The hydrogeochemistry of groundwaters beneath Lake Frome and surface waters in the GAB “mound” springs found on the Lake’s eastern shore have been studied by Draper and Jensen (1974). The study concluded that geochemistry of the brines and salts, found beneath and within Lake Frome, suggests that the source waters have mainly moved through the Tertiary and Quaternary aquifers, i.e. groundwaters sourced from the Willawortina and Eyre Formations. Contributions from the GAB “mound” springs were found to be relatively minor for the shallow groundwaters beneath the Lake.
STIFF PLOTS
GAB AQUIFER, EYRE FORMATION AND FRACTURED ROCK

FIGURE 3.20

Four Mile Region Conceptual Hydrogeological Model
Four Mile Region Conceptual Hydrogeological Model

EYRE FORMATION STIFF PLOTS

FIGURE 3.21
FIGURE 3.22

HCO3/CL RATIO SCATTER PLOT

- GAB east of Lake Frome
- GAB west of Lake Frome
- Fractured Rk
- Eye Fm
- Namba Fm
- Willawortina Fm
- Surface Water

4M0012 (Fractured Rock-aquifer beneath Four Mile deposit)

Close to Recharge

Groundwater flow path

[Graph showing HCO3/Cl ratio scatter plot with various groundwater sources and their respective Cl and HCO3 concentrations]
Sampling of the GAB spring discharges in the same study suggests that the spring waters comprise 90 to 95% carbonate rich GAB groundwater mixed with 5 to 10% subsurface brines. This mixing model is considered plausible given that the GAB discharge must move through the brine saturated shallower sediments in order to discharge to the surface.

Figure 3.23 presents stiff plots developed from data contained in the Draper and Jensen (1974) study, as well as one sample from the Northern Springs sourced from the South Australian Government’s Drillhole Enquiry System dataset. The plots show that the northern spring discharges have a higher concentration of Na and Cl than the southern springs, suggesting a higher degree of mixing between the GAB groundwaters and the Tertiary and Quaternary aquifer derived shallow brines in northern spring waters.

The inference from this study is that significant proportions of the salts contained in groundwater beneath Lake Frome are derived from evaporative concentration of salts in shallow groundwater beneath and adjacent the lake, whilst the mound springs are dominantly fed by the deeper GAB aquifer via structural conduits within the sedimentary units.

3.3.6. Summary

Several of the groundwaters within the Four Mile Region (Eyre, Namba and Willawortina Formations) demonstrate similar major ion compositions, with some variability between the formations. The Willawortina Formation has been sampled over a wider area and so displays increased variability to the east of the Poontana Inlier (increased calcium and bicarbonate).

Groundwaters from the fractured rock aquifer display no significant major ion domination across the Four Mile Region, however one sample suggests that in the immediate Four Mile area, the fractured rock aquifer has a very similar chemical composition to the Eyre Formation. Surface water composition is similar to the Namba / Eyre Formations but shows an increase carbonate probably due to being in contact with the atmosphere.

The GAB aquifer groundwaters are significantly different to those of the Eyre, Namba and Willawortina Formations indicating there is very little interaction, if any, with these upper units. Additionally, the anionic composition of the GAB aquifer groundwaters becomes dominated by bicarbonate rather than chloride to the east of Lake Frome, suggesting separate groundwater types within this aquifer on either side of Lake Frome.
FIGURE 3.23

STIFF PLOTS
LAKE FROME GAB "MOUND" SPRINGS

Northern Springs (Draper & Jensen, 1976)

Southern Springs (Draper & Jensen, 1974)

Lake Frome Mound Springs

Average

Cations meq/l

Anions

1,000

500

250

125

50

25

0

1,000

500

250

125

50

25

0
The hydrogeochemistry of groundwater and surface waters in the vicinity of Lake Frome supports the notion that the Lake forms a regional discharge sink for the Willawortina and Eyre Formation aquifers. In addition, discharging groundwaters from the GAB “mound” springs found on the eastern shore of the Lake are shown to comprise greater than 90% GAB aquifer groundwater, with only a very minor component of spring discharge water sourced from the Willawortina or Eyre Formations due to mixing with brines beneath the Lake or some other mechanism.
4. **Conceptual Hydrogeological Model**

4.1. **Overview**

Figure 4.1 presents a schematic of the conceptual hydrogeological model of the Four Mile Region, and is relevant to the following points of discussion.

The Four Mile Region hydrogeological and hydrogeochemical database consists largely of data collected by Quasar and Heathgate during investigations into the Four Mile and Beverley uranium deposits. For developing the current conceptual model, these data have been combined with existing geological data sourced from SARIG. The conceptual model builds upon earlier hydrogeological investigations which commenced with a study by, Kerr (1965) and were further developed by Draper and Jensen (1976) through the two Beverley Mine approvals processes (HGR, 1998 and Flow, 2007).

There are five main aquifer systems within the Four Mile Region: (i) Willawortina Formation, (ii) Namba Formation (Beverley aquifer), (iii) Eyre Formation (Four Mile aquifer), (iv) Cadnawowie Formation (GAB aquifer), and (v) fractured rock (basement aquifer). However, at the Four Mile deposit itself the Willawortina Formation is unsaturated.

4.2. **Groundwater processes**

4.2.1. **Four Mile region**

On a regional scale, groundwater recharge occurs in the west via the fractured rock aquifer where it outcrops as the Northern Flinders Ranges, and largely via creek washouts and lines on the ‘plains’ of the Frome Embayment. The fractured rock basement aquifers discharge to the sedimentary aquifers of the Frome Embayment.

Terminal discharge for the Four Mile Embayment groundwater system, which passes into the regional Eyre Formation aquifer, occurs largely via evaporative processes occurring where groundwater lies close to the surface, predominantly near and within Lake Frome and Lake Callabonna to the east. A brine has formed within the Quaternary and Tertiary sediments beneath and adjacent Lakes Frome and Callabonna as a result of salt accumulation in response to evaporative groundwater losses over geological time.
FIGURE 4.1

CONCEPTUAL HYDROGEOLOGICAL MODEL

Four Mile Region Conceptual Hydrogeological Model

CONCEPTUAL HYDROGEOLOGICAL MODEL

FIGURE 4.1
Drillhole data indicates that the Eyre Formation (host of the Four Mile deposit) forms the main aquifer in the immediate Four Mile area (i.e. west of the Poontana Inlier), although east of the Poontana Inlier, both the Willawortina and Namba Formations are saturated to some extent (the Namba in its entirety) and overlie the Eyre Formation. Water level data for the Eyre and Namba Formations suggest that the Poontana Inlier forms a north-south trending bounding structure to the east of the Four Mile embayment and directs groundwater flow northwards within the embayment.

4.2.2. GAB aquifer

The GAB aquifer is found between the Poontana Inlier and Lakes Frome and Callabonna, and lies beneath the Bulldog Shale aquitard at significant depth in relation to the Eyre, Namba and Willawortina Formations.

The available hydrogeochemical dataset strongly supports the notion that the GAB aquifer is hydraulically separate from the younger overlying formations, including the aquifers which host the Four Mile and Beverley deposits. This is supported by aquifer pressure data which demonstrates that the pressure in the Eyre Formation, at the northeastern margin of the Four Mile Embayment is approximately 40 m lower than the GAB aquifer pressure. As such, groundwater flow from the Eyre Formation into the GAB aquifer cannot occur. Similarly, the pressure in the GAB aquifer is also much greater than pressure in the Namba and Willawortina Formation aquifers.

The available hydrogeochemical dataset also shows that the GAB aquifer east and west of Lakes Frome and Callabonna has two different chemical signatures, with the Lakes forming a divide between the broader GAB aquifer groundwaters that are recharged along the Great Dividing Range and those GAB groundwaters west of Lake Frome in the closer Four Mile Region.

Groundwater elevation data suggests that a potentiometric depression of up to 40 m exists within the GAB aquifer beneath the eastern shore of Lake Frome, suggesting regional groundwater discharge in this area. Natural discharge is likely to occur as both as diffuse upwards leakage and evaporation from the lake bed, and via conductive faults within the overlying sediments to support GAB “mound” springs located on the eastern shore of Lake Frome. Pastoral use may have also contributed to the GAB aquifer potentiometric depression in this area. This potentiometric depression forms a strong hydraulic divide that separates the western GAB (Lake Frome) groundwaters from the broader GAB system to the east and north.
5. References


