THE HYDROGEOLOGY OF THE COASTAL MINING AREA, NIOLAM (LIHIR) ISLAND, PNG

By

Richard I.J. **Vogwill**[1], Stephanie **Williamson**[2]**,** and Jacqueline **Kote**[3]

[1]*Senior Principal Hydrogeologist, URS Australia Pty Ltd, Perth*

[2]*Senior Water Consultant, Rio Tinto Technical Services, Perth*

[3] *Mine Hydrogeologist, Lihir Management Company, Lihir Gold Mine, New Ireland Province, PNG*

[1]*URS Australia Pty Ltd, Level 3, 20 Terrace Road, East Perth, WA, Australia 6004, Ph 08 9326 0247, Fax 08 9221 1639, richard_vogwill@urscorp.com*

Abstract

Open-pit mining commenced at the Lihir Gold Mine in 1997 and dewatering in 1998. The ore bodies (Minifie and Lienetz) occur in a collapsed volcanic crater (which contains a remnant geothermal system) breached by the ocean. Successful open-pit dewatering has been achieved under very adverse mining conditions, including, high groundwater temperatures, seawater intrusion affecting dewatering efficiency and interaction with the underlying geothermal system.

A seawall will occur between the ultimate pit perimeter and the ocean. The hydraulic connection between the mine and the ocean through this seawall is currently being studied. The integrity of this seawall is imperative to long-term mining success and the coastal hydrogeology of the seawall and mine area is actively being studied.

BACKGROUND AND SETTING

Niolam Island (commonly referred to as Lihir Island) is the largest island of the Lihir Group and is located in the Tabar-Feni volcanic island-arc chain (a complex tectonic convergence zone) in the New Ireland Province of Papua New Guinea, about 900kms northeast of Port Moresby (Figure 1). Geothermal activity and epithermal gold mineralisation occur on Niolam Island. The island is estimated to be 0.2 to 3.7 million years old (Pliocene to Recent age) and comprises five volcanic landforms.

The collapsed caldera of the largest of these, the Luise Volcano, is the most prominent topographic feature (elevation 600m ASL) on the island and was breached on the eastern side by the ocean to form Luise Harbour (Figure 1). The Luise Caldera "*is postulated to have formed by the failure of the volcanic edifice in a Mt Helens style eruption, with the seaward sector of the volcanic cone collapsing into Luise Harbour*" (Kidd and Robinson, 2004). Bathymetry surveys show the trace of the submarine debris flow of this collapsed material into Luise Harbour.

Gold mineralisation in the Luise Caldera was discovered in 1982. Kennecott Explorations (Australia) completed two mining feasibility studies of the Ladolam ore bodies (Minifie and Lienetz, about 2km long, 1.5km wide and up to 300m deep) in 1989 and 1992. The feasibility of mining an additional major ore body (Kapit) was proven in 2003.

GEOLOGY AND GROUNDWATER GEOLOGY

General Geology

The ore bodies are hosted by volcanic breccias and intrusives that are underlain by volcanic basement rocks (Figure 1). There has been significant alteration of the host rocks, such that classification is by "ore type" rather than rock type. The host rocks have been altered in two distinct episodes, an early porphyry-style deep alteration and a later, shallower epithermal alteration. The porphyry-style alteration generally occurs at depths greater than 100m below sea level. Late stage epithermal alteration overlies and overprints the porphyry-style alteration and hosts the gold mineralisation (Davies and Ballantyne, 1987).

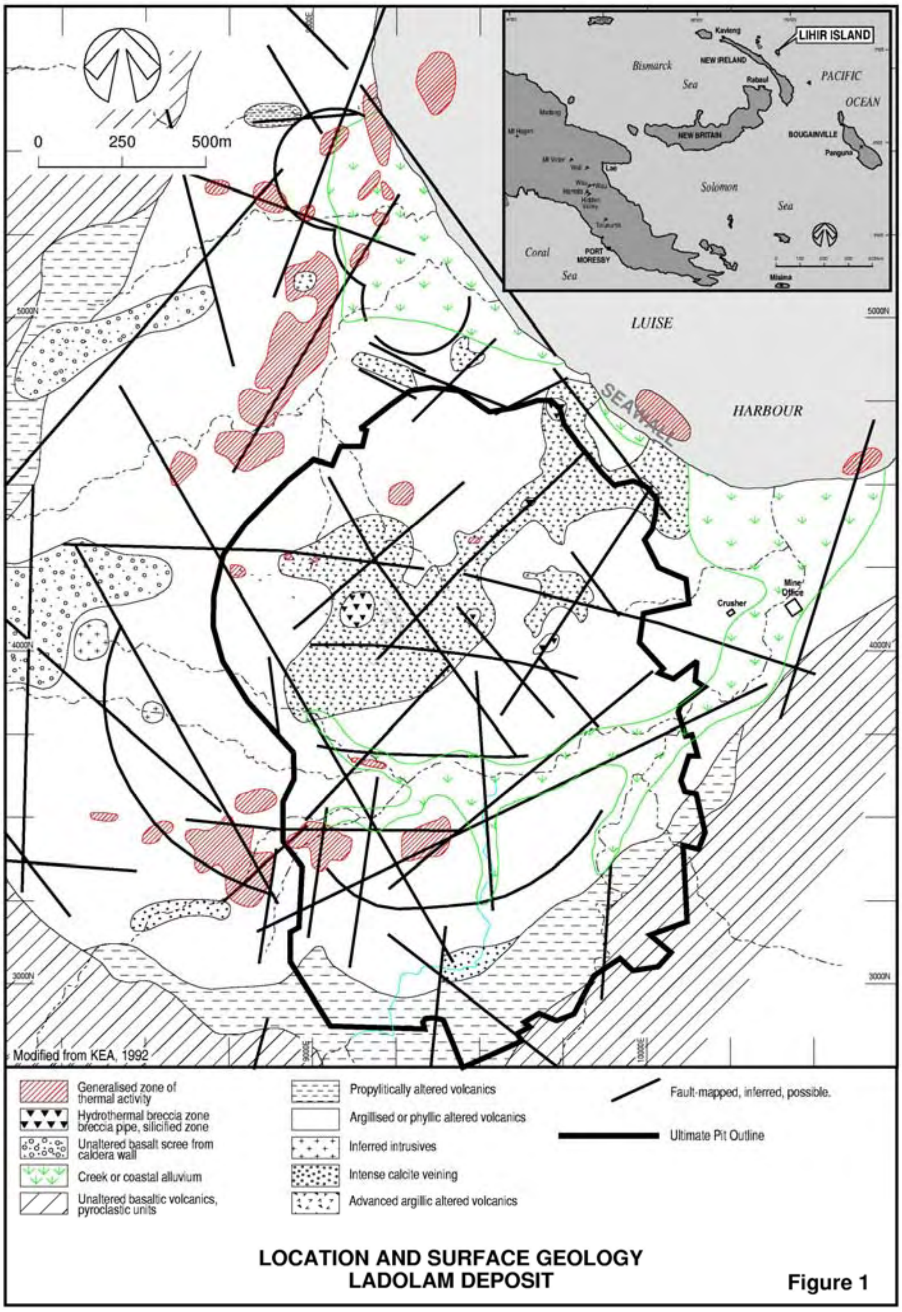

Figure 1 - Location and Surface Geology (modified from KEA, 1992)

Aquifer Types and Occurrence

Hydrogeologically, the three most important ore types (Table 1) are:

- The Siliceous Breccia (SBX), open, vuggy, crumbly and fractured texture, aquifer;
- The Boiling Zone (BZ), pin-point porosity texture, open cavities and breccia, aquifer; and
- Sealed zones (S - sealed or AHS – anhydrite sealed), which form semi-permeable basal aquitards under large areas of the caldera.

The major geological structures in the caldera comprise a series of northwest-trending transform faults and attendant secondary faults (Figures 1 and 2), probably related to both volcanic emplacement and caldera collapse. Steeply dipping ring structure faults and fractures occur locally along the inside perimeter of the caldera walls.

Two general types of aquifers (Table 1, Figures 1 and 2) largely control groundwater occurrence and flow:

- Secondary permeability features such as sub-vertical major structures (fault zones, shear zones and fractures); and

- The “primary” permeable rock textures, such as BZ and SBX.

In some areas, these two aquifer types intersect and result in a high permeability. A good example is the Minifie Shear Zone, a sub-vertical shear zone (containing SBX/BZ) that occurs under and parallel to the Ladolam Valley in a SW-NE orientation and underlies the Minifie pit. Based on the historical locations of thermal submarine discharges under Luise Harbour (Figure 1), it is probable that this shear zone extends offshore and is probably in hydraulic connection with the ocean. The Minifie Shear is the major aquifer system under the southern mining area.

The other ore and rock types in the mine area are usually clayey and have a low primary permeability.

Table 1
Summary of Aquifer Types

Aquifer Zone	Occurrence	Orientation	Comments
SBX/BZ, AOPBZ	Minifie-Ladolam-Lienetz area, especially in troughs in AHS and at the intersection of vertical lineaments.	Sub-horizontal to tabular, series of small layers or quite thick.	Highly permeable major aquifer. May continue through sea wall.
AHS aquifer	Occurs near the intersection of AHS with vertical structures. Elsewhere is an aquitard	Vertical and sub-horizontal.	High permeability locally near vertical structures. Underlies open pits.
Ring Structure	Along the eastern and southeastern margins of Ladolam Creek Valley.	Near vertical dipping into centre of caldera.	Moderately permeable. Generally marks the limits of the SBX/BZ.
Vertical Structures	Throughout the deposits.	Near vertical. Recent work also suggests shallower angles locally.	Adds significant permeability to all rock units, especially BZ, AHS, and SBX.
Weathered Clay	Uppermost section of weathered bedrock.	Sub-horizontal.	Significant permeability in fractured weathered rock. Hydraulic connection with recent alluvium.
Recent Alluvium	Along Ladolam Creek Valley.	Horizontal in-filling.	Highly permeable but of limited extent.

(modified from Dames & Moore, 1998)

Aquifer Parameters

Due to safety and operational constraints, aquifer tests are not routinely completed on new pumping wells. However, aquifer parameters (Table 2) have been derived from: (i) large-scale pumping/injection tests completed during the feasibility studies; and (ii) measured aquifer responses during the early stages of dewatering.

Table 2
Summary of Injection/Pumping Tests and Derived Aquifer Parameters

Well	Area	Test Time (days)	Test Rate (L/sec)	T (m^2/day)	S (-)	K (m/day)*	Aquifer Zone
DCM-1	M	19.8	31	3000	0.002 to 0.08	10 to 40	Breccia
DCM-2	M	12	33	3000	0.0005	10 to 40	Breccia
DCM-3a	L	23.5	30	400 to 800	0.005 to 0.01	40	BZ
DCM-3b	L	9.9	35	1800 to 2700	0.0004	40	BZ
G1	L	17.0	36	550 to 3600	0.0005	0.01 to 10	AHS
G4	M	3.0	22	2000	0.01	0.01 to 10	AHS
L212	C	4.0/2.0	29/30	550	0.0008	0.01 to 10	AHS
PB-1	La	10.0	42	2500 to 3500	0.0001 to 0.005	10 to 40	Breccia
L312	M/L	0.08	1.4	800	-	8	Low K areas
PW1 to 4	La	8	326	500 to 700	0.01 to 0.3	2 to 7	Structure/SBX
PW1 to 4	La	32	260	700 to 1200	0.03 to 0.3	2 to 12	Structure/SBX

Notes: (from Williamson and Vogwill, 2000); *flow modelling values; M=Minifie; L=Lienetz; La=Ladolam Creek; C=Coastal; T=transmissivity; S= storativity; K=permeability, AHS=anhydrite sealed zone.

Conceptual Aquifer Occurrence and Hydrogeological Model

The conceptual hydrogeology of the deposit comprises a dual-aquifer system – sub-vertical structures and permeable rock textures. The occurrence of aquifer zones is structurally controlled and the resulting permeability of the rocks is therefore strongly anisotropic. The major structures are thought to: (i) result in hydraulic connection between adjacent areas of the deposits; (ii) form permeable links between sub-horizontal aquifer zones; and (iii) form links between the underlying geothermal system and the upper groundwater/geothermal system.

Long term pumping and injection tests during the feasibility studies and the initial dewatering results confirm that the structures are significant permeable features, often related to the formation of the SBX/BZ aquifer zones. The SBX/BZ zones are permeable, confined aquifers and based on thermal discharge areas in Luise Harbour, they could extend offshore. The SBX/BZ frequently occurs in troughs (which coincide with structures) at the top of sealed zones.

Below the top of the sealed zone, many (but not all) sub-vertical structures may reduce in permeability and this is probably the lower boundary of the most active groundwater flow system. A large groundwater salinity gradient occurs across the boundary. Locally, some permeable structures extend at depth below the sealed zones, and these are the main targets for the geothermal mitigation measures and geothermal exploration.

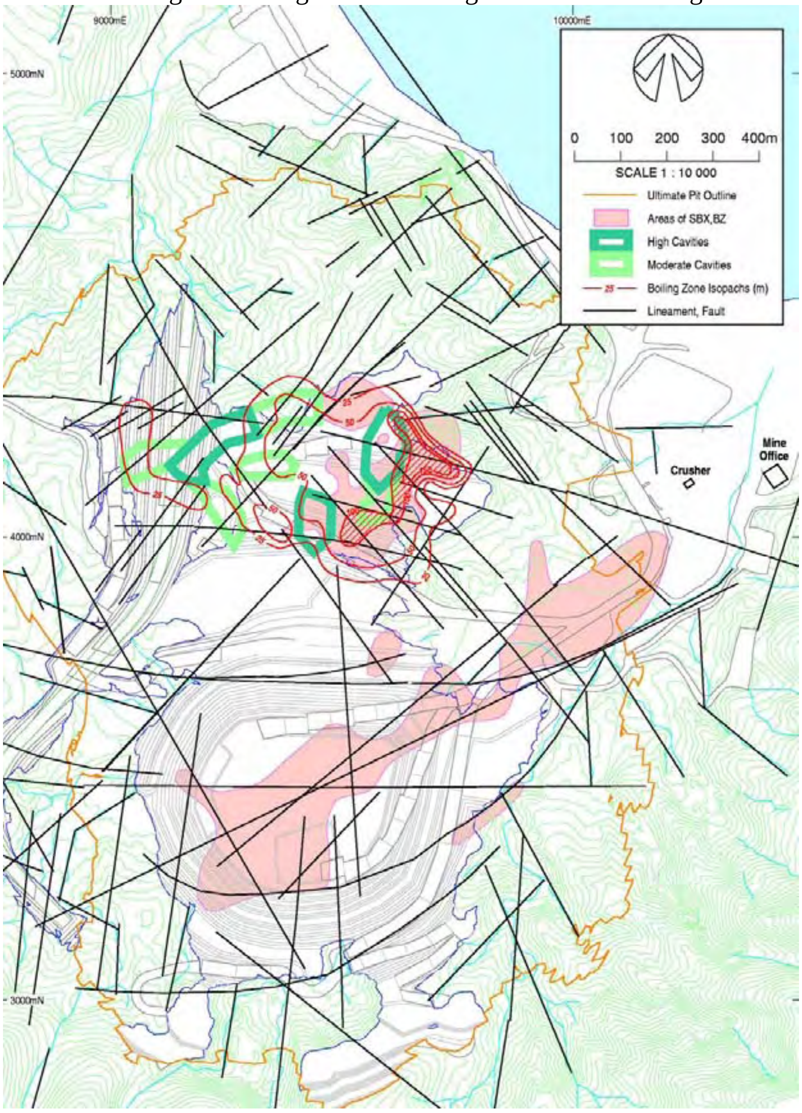

Figure 2 - Conceptual Aquifer Occurrence (modified from Dames & Moore, 1998)

Groundwater Levels and Temperatures

The initial groundwater levels in the Minifie and Lienetz mining areas were within 20m of the pre-mining ground surface, while at the coast they were at ground surface (sea level assumed at elevation of 1,000 m RL). Groundwater flow was generally towards Ladolam Valley and then towards Luise Harbour. During the early stages of dewatering, an elongate drawdown trough began developing along the Minifie Shear, where all of the early pumping wells were located. Since 1999 and with the addition of pumping wells east of the Lienetz pit, the drawdown trough now extends northwards into the Lienetz area (Figure 3).

Due to the geothermal nature of the area, groundwater temperatures are high and locally supercritical in that they fall above the boiling point-pressure curve. The distribution of groundwater temperature was initially determined from temperature-depth surveys in exploration drillholes and monitoring bores. The highest temperatures are in the western and northwestern areas of the deposit and these areas are termed geothermal upflow areas (Figure 8). ‘Tongues’ of hot water in the upper Ladolam Valley indicate deep permeable structures along which geothermal outflow occurs. Outflow areas of hot geothermal fluids occur along the coast and under Luise Harbour - these are areas of groundwater discharge (Figure 1).

Near–surface aquifers within the deposit are rapidly recharged by rainfall, for example where the Minifie Shear subcrops under the alluvial deposits. Major permeable structures extend upwards into the near-surface ore types and are in good hydraulic connection with the overlying alluvium and drainage features. This results in rapid recharge to near-surface aquifers during heavy rainfall and a good correlation between rainfall and groundwater levels.

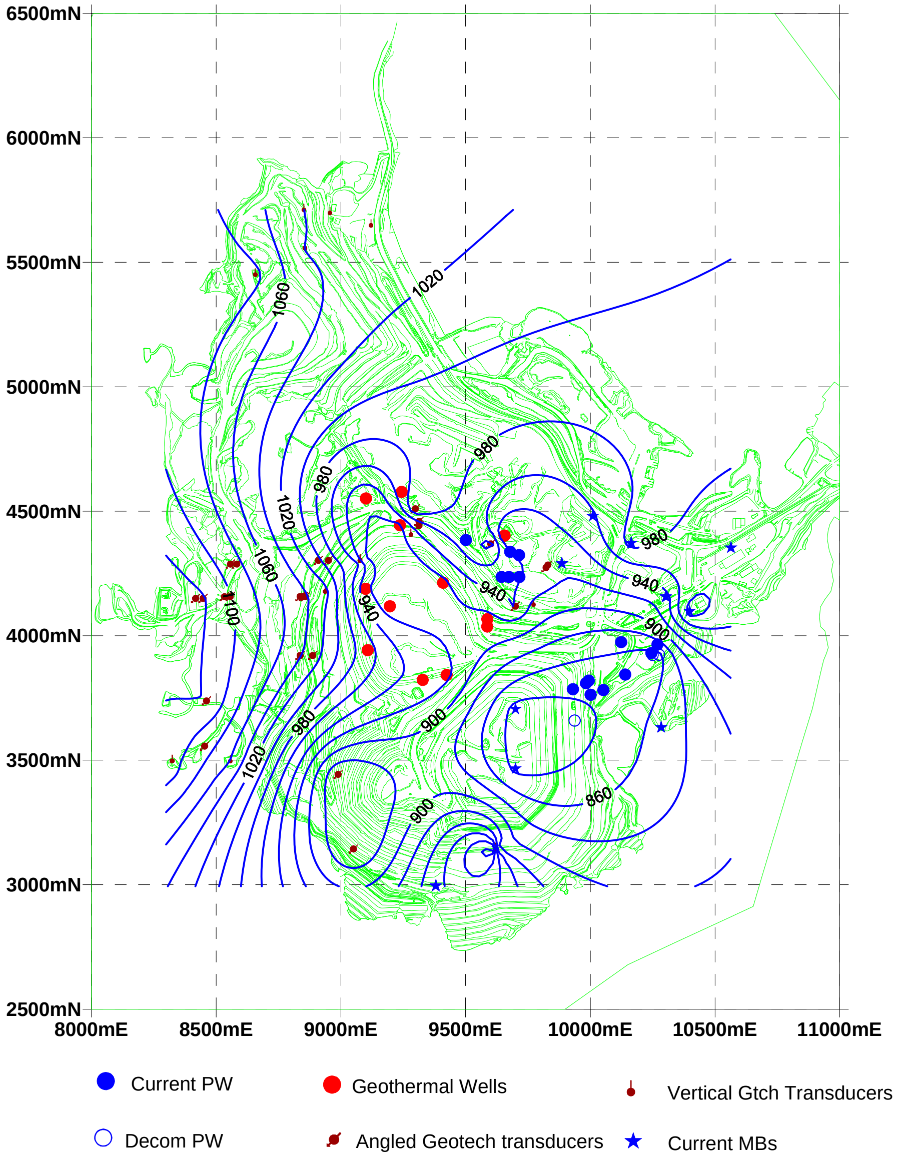

Figure 3 - Current (March 2005) Groundwater Elevations (mRL)

Basic Fluid Chemistry

The groundwater chemistry is complex due to the geothermal nature of the area and proximity to the ocean. Ascending geothermal fluids (upflow areas) occur in the west and northwest of the mining area and these fluids underlie the deposits at depth. In near-surface, higher-permeability, areas large rainfall recharge occurs and dilutes these geothermal fluids with cooler meteoric water. This results in lenses of 'fresher', cooler groundwater floating on hot, denser, more saline geothermal fluids.

The deepest sampled geothermal fluids have a neutral pH and TDS content up to 60,000 mg/L. Most components in these fluids indicate that they are distinct from seawater and from seawater altered in other geothermal systems. East of the geothermal upflow areas and in areas with a high permeability, infiltrating meteoric water dilutes these fluids; therefore, the cooler 'mixed' groundwater is significantly less mineralised than the geothermal fluids. The initial groundwater sampled from the dewatering and monitoring bores had a near-neutral pH and a TDS content of about 20,000mg/L.

SUCCESSFUL OPEN-PIT DEWATERING IN AN ADVERSE MINING ENVIRONMENT

Mining Conditions

Open-pit mining at the Lihir Gold Mine commenced in mid-1997 (Minifie Deposit), within the active geothermal environment of the Luise Caldera. At depth locally in the mining area, the highest measured groundwater temperatures are above 250°C at a depth of 300 m (Figure 8). At the commencement of mining, the groundwater and rock temperatures in the Minifie area were generally well above 60°C (Figure 8), which provided a technically challenging and potentially unsafe mining environment, with numerous thermal discharges through the pit floor. Of particular concern was the possible occurrence of a geothermal-type discharge related to unloading by mining, combined with high rock/groundwater temperatures and pressures under the open-pit.

Dewatering System

As all ore bodies occur below the water table, mine dewatering is required for efficient and safe mining. To date, successful mine dewatering has been achieved using a series of pumping wells, mainly located outside the active mining area (Figure 3), with groundwater discharged into the ocean through a series of pipelines and diversion drains. These wells, generally constructed by geothermal drilling contractors, are equipped with high-temperature (oil field type) electro-submersible pumps (up to 1,100 kW). As discussed below, the wells nearest the coast are pumping a large percentage of seawater.

Groundwater Abstraction

Since 1998, average total pumping rate from the dewatering system has gradually increased to about 650 L/sec (Figure 4). The pumping rates from individual dewatering bores range from 50 to 130L/s (average 50 to 60 L/sec – Figure 5); typical pumping water levels are 100 to 200m deep.

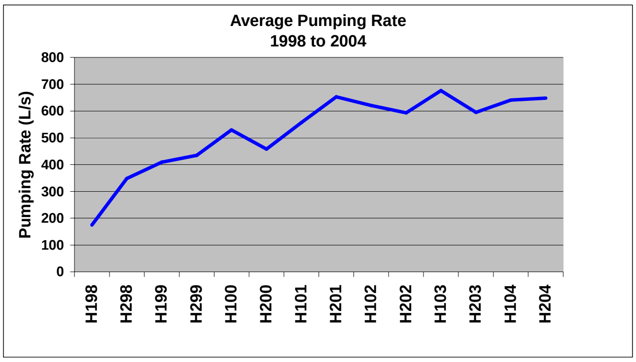

Figure 4 - Average Pumping Rate 1998 to 2004 (RTTS, 2005)

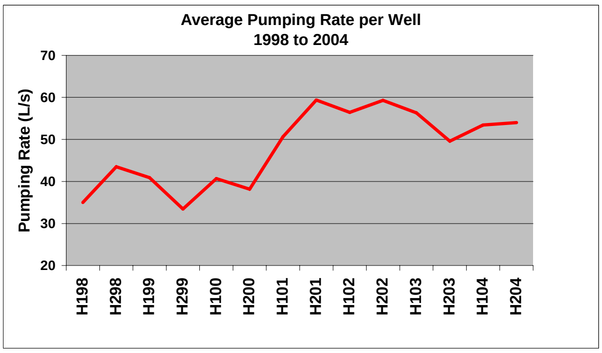

Figure 5 - Average Pumping Rate per Well 1998 to 2004 (RTTS, 2005)

Temperature of Abstracted Groundwater

Currently, the temperature of the pumped fluid ranges from about 60°C to 100°C and is generally decreasing in most areas. In the three Lienetz pumping wells, initial groundwater temperatures were above 100°C and the fluid was boiling in the rising main as the pressure of the ascending groundwater reduced. The

Lienetz fluid temperatures are decreasing, due to increasing seawater and meteoric components, but are still above 90°C (Figure 6).

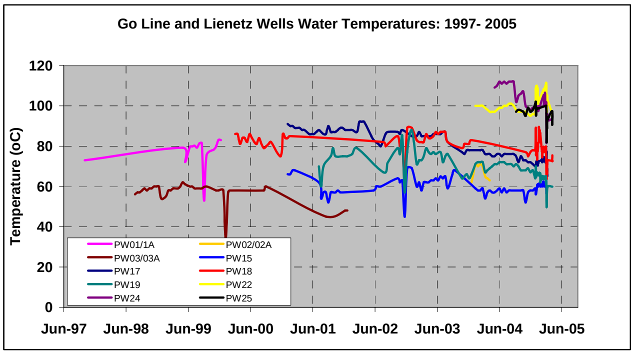

Figure 6 - Out of Pit Pumping Well Temperatures 1997 to 2005 (RTTS, 2005)

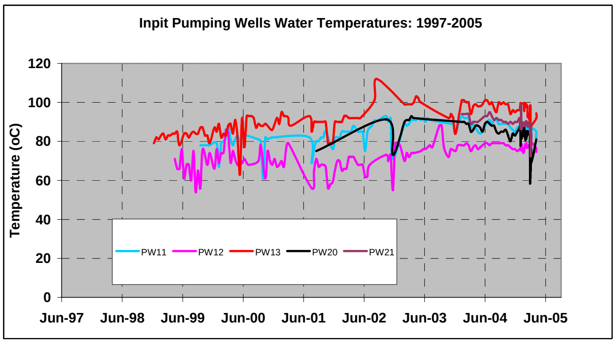

Figure 7 - In Pit and Near-Pit Pumping Well Temperatures 1997 to 2005 (RTTS, 2005)

Quality of Abstracted Groundwater

The composite fluid discharged from the pumping wells is a mixture of groundwater, seawater and geothermal fluids and contains 7,000 to 40,000 mg/L total dissolved solids (TDS). This fluid has a near-neutral pH and the principal chemical constituents are chloride, sulphate and sodium ions (Geokem, various). There are also high concentrations of calcium, magnesium and bicarbonate. The discharge flows into Ladolam Creek and diversion channels and ultimately to Luise Harbour.

GEOTHERMAL RESOURCES AND DEWATERING INTERACTION

Geothermal Resource and Power Generation

According to Allis (2003): *" A substantial high-temperature resource exists beneath the Luise Crater…. Proven temperatures range to over 300°C at 1 km depth (0 mRL) and the area with temperatures in excess of 200°C at 800 mRL is 2-3 km^2. This area lies west and north of the present Minifie pit."* A schematic NW-SE cross-section through the geothermal system (Allis, 2003) is shown in Figure 8.

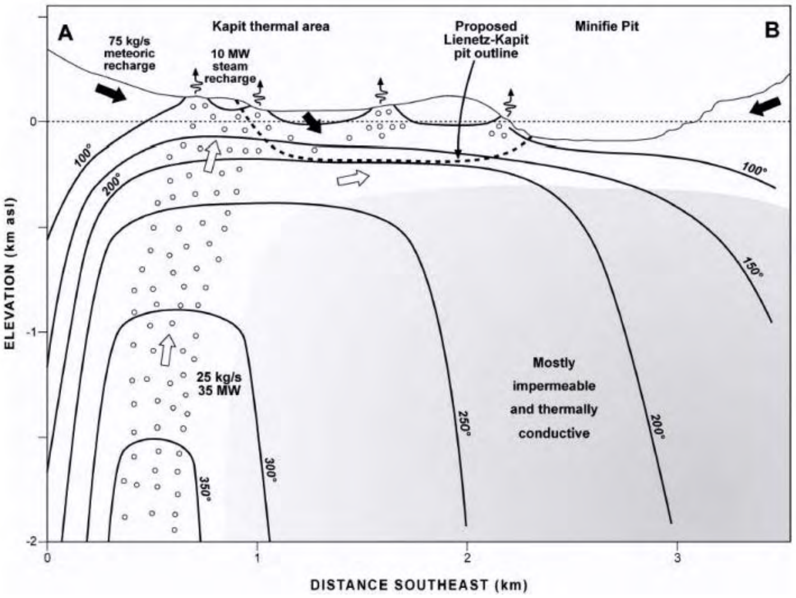

Figure 8 - Schematic NW-SE Cross-Section of Lihir Geothermal System (Allis, 2003)

The geothermal environment within and under the mining area has been extensively studied to both minimise mining risk and develop the geothermal resource as a power supply (Allis, 2003). Numerous geothermal exploration and production wells have been drilled to delineate the geothermal resources and provide production for geothermal power. To date, a 6 MW geothermal power station has been in operation for 5 years and a 35 MW geothermal power station has recently been commissioned. Feasibility studies for an additional geothermal power station are ongoing. The use of geothermal power significantly improves the economics of the mining operation.

Geothermal Aspects of Dewatering

The sealed zones form an approximate sub-horizontal divide between the groundwater/geothermal system that impacts on mining (above) and the geothermal resource that can be developed as a source of power (~1 km deep). However, as previously mentioned, there is a hydraulic connection between these two systems, provided by the sub-vertical structures. Accordingly, the pumping from one system affects the other and vice-versa. *"Monitoring of deep geothermal pressures since mine development started shows that at least the eastern part of the geothermal system (i.e. west of Minifie pit) has de-pressured by about 7 bars, equivalent to about 80 m of hot water head loss."* (Allis, 2003). This drawdown in the deep geothermal system has been caused by: (i) a component of the pumping well discharge being derived from geothermal fluids (about 10 to 12%); and (ii) geothermal production from deeper zones to provide geothermal energy. Figure 9 (Allis, 2003) shows the relationship between the deeper and shallower systems and the drawdown caused by pumping activity. There is an apparent 1-2 year time lag between the start of mine dewatering and a hydraulic response in the deeper system. This type of response would fit with "leaky" sealed zones caused by sub-vertical structures continuing to depth.

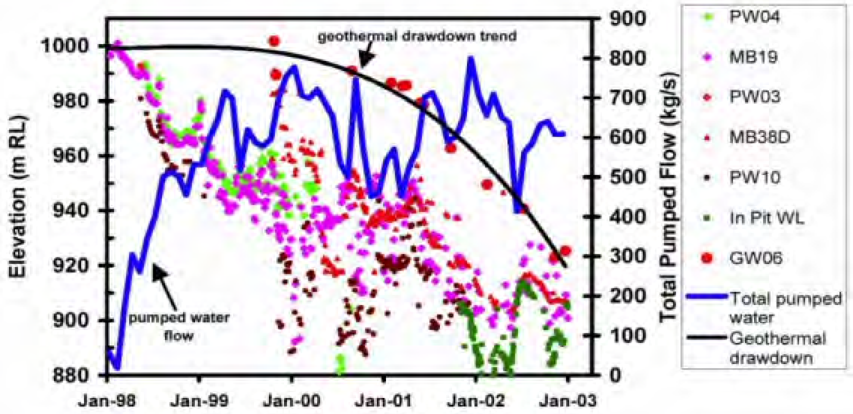

Figure 9 - The Response of the Geothermal System to Groundwater Abstraction (Allis, 2003)

Geothermal – Dewatering Interaction

The dewatering strategy has to include geothermal mitigation measures, to reduce the risk of geothermal eruptions or blowouts. Groundwater level lowering causes the formation of steam by boiling and the resulting pressure build-up of steam needs to be reduced (via steam relief wells) to minimise the potential for geothermal eruptions.

As seen above, there is an apparent hydraulic interaction between the geothermal system and the groundwater system. That is, that mine dewatering causes drawdown in the underlying geothermal system. Too much drawdown in the geothermal system could impact on geothermal resource recovery, however it is doubtful that groundwater pumping will impact deep geothermal resources.

COASTAL HYDROGEOLOGY AND THE SEAWALL

A better understanding of the hydrogeology of the coastal area along Luise Harbour is essential as it is assumed that a "seawall" left between the ultimate pit perimeter and Luise Harbour will act as a barrier to water flows from the ocean into pits that are eventually about 300m below sea level. A geotechnical study of the seawall was completed in 2000 and currently (2005) detailed studies of the seawall are in progress to determine the geotechnical properties of the wall and the hydraulic connection between the ocean and the mining area.

Much of the long-term dewatering strategy for the remaining mine life will focus on minimising inflows through the seawall area.

Groundwater Levels and Tidal Efficiency

Pre-mining groundwater elevations indicated a groundwater flow towards the ocean. Since dewatering commenced, this flow direction has been reversed and flow is now inland towards the pumping wells in Ladolam Valley (Figure 3).

Groundwater monitoring bores along the coast are located at the southeastern end of the seawall, across the Minifie Shear. As a result of pumping in the Ladolam Valley, these bores have groundwater levels below sea level, indicating that the drawdown cone caused by dewatering has migrated past the coastline and under Luise Harbour (Figure 10, sea level at 1,000 m RL).

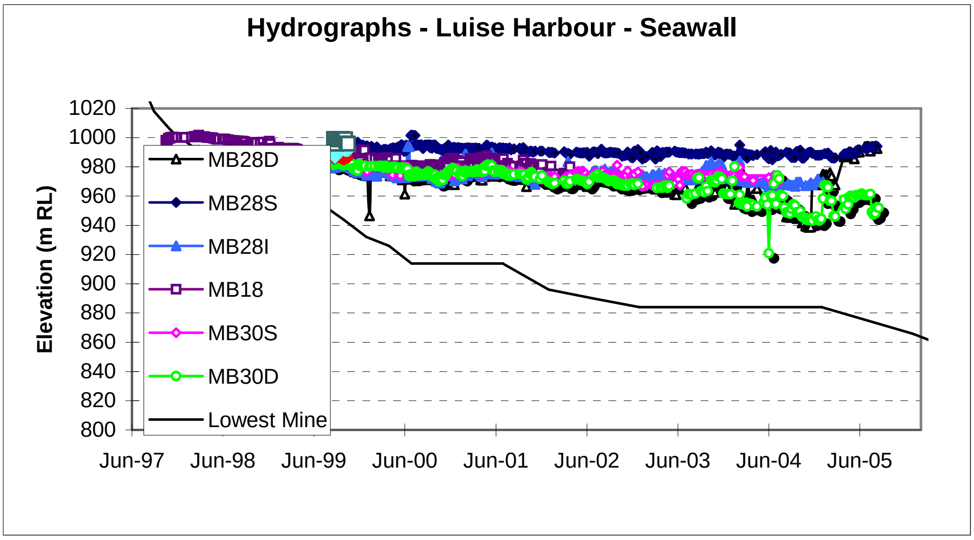

Figure 10 – Groundwater Elevations – Luise Harbour/Seawall Area

Early groundwater studies indicated that groundwater levels in certain areas of the deposit have a strong correlation to ocean tides. This was established by continuous monitoring of tidal levels and groundwater levels for a period of days. Near the coast, the tidal efficiency is above 30%, but decreases rapidly inland (Figure 3). Contours of tidal efficiency in Figure 3 show that tidal efficiency generally decreases away from Luise Harbour. However, a number of bores in the Ladolam Valley showed a reasonably large tidal efficiency, even though they are 2 to 3 km from the coast. This is a function of a permeable corridor (the Minifie Shear) that occurs under the valley and extends under the coast.

In addition to high tidal efficiency along the Ladolam Vallet towards the Minifie area, the contours of tidal efficiency also follow approximately east-west structures that extend from the Ladolam Valley towards the Lienetz deposit (Figure 11). This also implies an enhanced hydraulic connection between the Lienetz area and the ocean, but not through the seawall where the tidal efficiency is small (Figure 11).

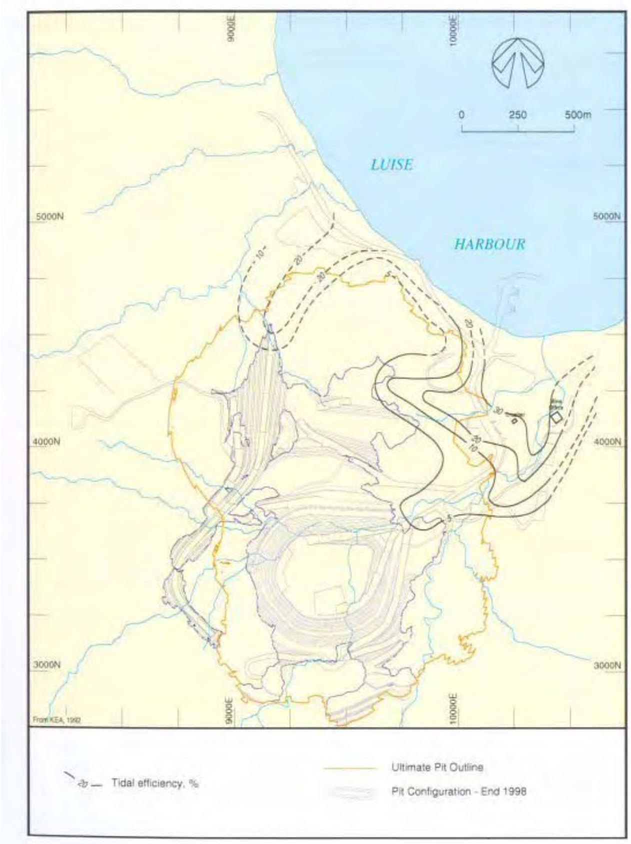

Figure 11 - Tidal Efficiency (Dames & Moore, 1998)

It is known from thermal imagery surveys that there are numerous submarine discharges of geothermal fluids and groundwater under Luise Harbour (Figure 1), presumably from aquifer zones that extend offshore, like the Minifie Shear that subcrops under the harbour. These occurrences and the distribution of tidal efficiency near the coast suggest that there is the potential for seawater to enter the mine via these aquifer zones.

Seawater Intrusion and the Quality of Dewatering Discharge

Various groundwater chemistry studies of the pumping well discharge indicate that seawater intrusion is occurring in both the Minifie and Lienetz areas. This seawater is presumably entering the Minifie Shear under Luise Harbour and migrating inland under the coast. The amount of seawater being pumped affects dewatering efficiency and increases costs because of re-circulation and corrosion of electro-submersible pumps.

For the past five years, the percentage of seawater being pumped in the discharge has increased significantly. Some pumped wells near the coast are currently pumping almost 60% seawater, from initial values of less than 10% (Figure 11).

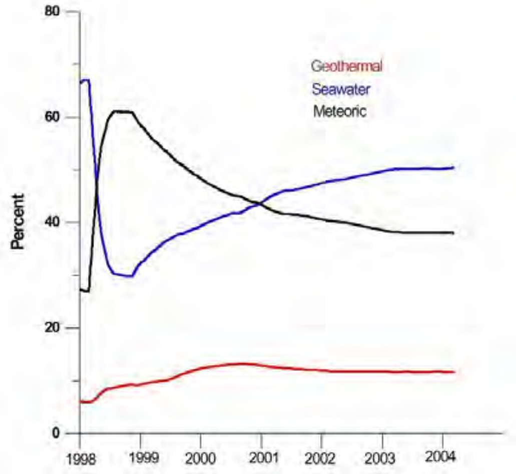

Figure 11 - Components of Pumped Fluid (after Allis, 2003)

Based on current groundwater levels (Figure 3), the cone of depression created by the dewatering has migrated under Luise Harbour. Monitoring bores in the Minifie Shear at the coast indicate groundwater levels up to 50 m below sea level. For this magnitude of drawdown to occur at the coast, the hydraulic connection between the ocean and the shear zone must only be moderate.

Seawater intrusion has also migrated into the Lienetz area. Chemical analyses of the Lienetz pumping wells discharge indicate a gradually increasing percentage of fluid being derived from the ocean (currently about 25%). Presumably, this seawater is migrating along the E-W structures extending from the Ladolam Valley into the Lienetz area.

Evaluating Seawall Integrity

The integrity of the seawall between the open pits and the ocean is an important aspect of the mine design at Lihir Gold. The mine has been designed assuming that this wall will be stable and that seawater flow through it will not flood the mine. The two major geotechnical studies of the seawall are being used to characterise the geotechnical and hydrogeological aspects of the seawall.

Historically, groundwater monitoring (standpipe) bores were not installed along the northwestern section of the seawall because of difficult drilling conditions (very hot groundwater temperatures at depth) along the Coastal Geothermal Zone (Figure 1) and other drilling priorities. However, as part of the current geotechnical drilling program in the seawall area, vibrating wire transducers are being installed in a number of piezometers throughout the seawall. This work has included packer injection tests to determine rock and defect permeability. The results of this work are not yet available.

Conceptually, there are two main types of aquifers that could connect the ocean to the pits through the seawall – areas of SBX/BZ and sub-vertical structures - but this has yet to be confirmed. Based on geological cross-sections from the 2000 preliminary geotechnical study, there are areas of SBX/BZ that occur in and under the seawall area. However, these aquifers do not appear to have a direct hydraulic connection to the ocean, as they occur in lenses that are largely sealed from the ocean by clayey caprock and the underlying sealed zones.

A large number of sub-vertical structures (both perpendicular and parallel to the coast) are thought to occur in the seawall area (Figure 2) and the hydrogeological characteristics of these are currently being determined from the recent geotechnical drilling program. There is geochemical evidence that seawater is entering the Lienetz pumping wells from the Minifie Shear, but not through the seawall. The results from the recent seawall geotechnical drilling and testing program will be used to clarify the integrity of the seawall as a barrier to water flow into the mining area.

Seawater Flow and Recharge Characteristics of the Minifie Shear

Based on results to date, the Minifie Shear appears to the main conduit allowing seawater to enter both the Minifie and (to a lesser extent) Lienetz pumping wells. The pumping wells nearer the coast form an artificial pumping barrier, which helps to limit the landward migration of seawater. These wells pump the highest percentage of seawater and as a result, a corrosive environment occurs in these wells and pumps need more frequent maintenance. It would be advantageous to create an artificial pumping barrier closer to the coast, however to maintain mining infrastructure effectiveness this is not possible and therefore seawater has migrated considerable distances inland.

The exact dimensions (width and depth) of the Minifie Shear are unknown. Based on the results of aquifer tests and dewatering results, the range of permeability of the shear is thought to be between 5 and 40 m/day (Table 2). The current hydraulic gradient (Figure 3) between Luise Harbour and the Minifie Pit appears to be in the range 0.1 to 0.3, very steep because of the intensive pumping in the Ladolam Valley. Assuming 50% of the pumped fluid is seawater (325 L/sec) and based on the current hydraulic gradient and a range of permeabilities, approximate calculations of the dimensions of the Minifie Shear are summarised in Table 3.

Table 3

Possible Flow Characteristics of the Minifie Shear

Assumed Seawater Inflow (50% of total pumping rate – L/sec)	Hydraulic Gradient (-)	Permeability (m/day)	Flow Area (m^2) (width x saturated thickness)	Calculated Flow (L/sec)
325	0.2	1	390x360	325
325	0.1	5	185x300	321
325	0.2	10	55x250	318
325	0.1	10	95x300	330
325	0.2	20	30x250	347
325	0.1	20	60x250	347
325	0.2	40	25x150	347
325	0.1	40	25x300	347

Based on past drilling results, the shear can be at least 300 m thick and occurs across a significant width of the Ladolam Valley. Given this, it appears that in order to match the assumed inflow of seawater (50% of 650 L/sec), the permeability of the shear is less than 10 m/day and the width is probably 150 to 250m (Table 3).

Based on Q= k’ dh/dl, where Q= vertical flow per unit area of aquitard; k’ = vertical permeability of aquitard; dh = difference in head (m) above and below aquitard; and dl = thickness of aquitard (m); some simplistic estimates of the leakage parameters for the Luise Harbour floor and underlying aquitard (assumed as argillic rocks) can be made (Table 4). Under steady-state conditions, the amount of seawater leaking into the Minifie Shear is assumed as 50% of 650 L/sec or 325 L/sec (28,080 m^3/day). Table 4 summarises a set of assumed parameters (vertical flow area, vertical permeability, head difference and aquitard thickness), which satisfy this assumed leakage rate.

Table 4

Vertical Leakage Characteristics – Luise Harbour to the Minifie Shear

Assumed Total Seawater Inflow* (m^3/day)	Assumed Intake Area for Vertical Flow under Harbour (m^2)	Assumed Inflow Per Unit Area ($m^3/day/m^2$)	Assumed Vertical Permeability, k’ (m/day)	Assumed Head Difference - Luise Harbour and Minifie Shear, dh (m)	Assumed Aquitard Thickness, dl (m)	Calculated Inflow Per Unit Area ($m^3/day/m^2$)**
28,080	**10,000**	2.8	**0.5**	**30**	**5**	3.0
28,080	**100,000**	0.3	**0.2**	**20**	**15**	0.3
28,080	**1,000,000**	0.03	**0.2**	**10**	**45**	0.04
28,080	**10,000**	2.8	**1.0**	**30**	**10**	3.0

28,080	**100,000**	0.3	**0.5**	**40**	**60**	0.3
28,080	**1,000,000**	0.03	**0.1**	**30**	**100**	0.03
28,080	**10,000**	2.8	**0.5**	**5**	**10**	2.5
28,080	**100,000**	0.3	**1.0**	**10**	**30**	0.3
28,080	**1,000,000**	0.03	**0.1**	**30**	**100**	0.3

* assumed as 50% of 650 L/sec or 28,080 m^3/day; ** for the range of assumed values shown to the left.

For a realistic range of heads and thicknesses, the vertical permeability of the intake zone under Luise Harbour varies between 0.1 and 1 m/day, but this range of values is not unique. From this very simplistic approach, it appears that to achieve a realistic value of vertical permeability for the Minifie Shear below Luise Harbour, the intake area must be reasonable large (perhaps up to 1,000,000 m^2 or 1km^2).

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