MULTI-LEVEL DATA AS A KEY COMPONENT FOR A HYDROGEOLOGICAL CONCEPTUAL MODEL OF AN UNDERGROUND MINE

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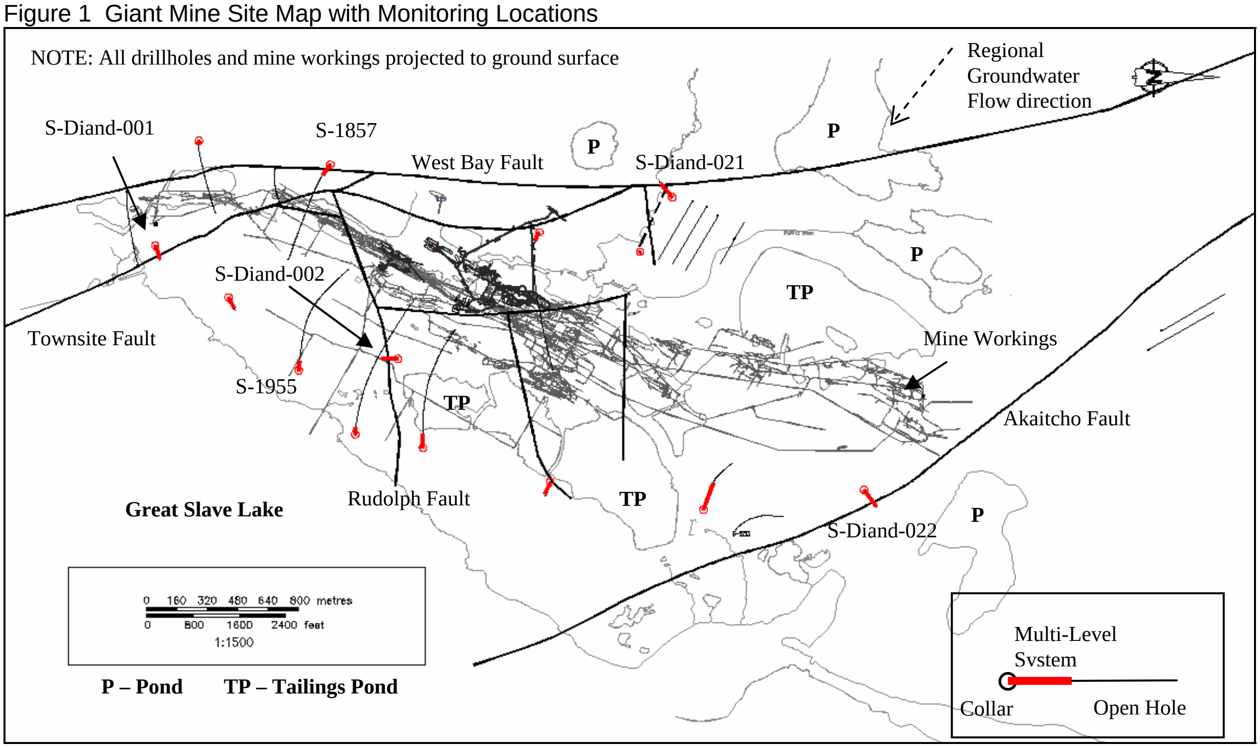
ABSTRACT
Development of reasonable hydrogeologic conceptual models is an integral step in any hydrogeological study. For underground mines in the Canadian Shield, where the presence of distributed workings, faults and surficial tailings impoundments exist, an understanding of both horizontal and vertical gradients is required. As part of the closure plan for the Giant Mine, located just outside Yellowknife, Northwest Territories along the shore of Great Slave Lake, a series of fourteen multi-level monitoring systems were installed to provide information on hydraulic gradients, as well as to act as a regional monitoring system after re-flood. Multi-level systems targeted to cross large-scale faults show that faults can act as either barriers or conduits for flow, possibly acting to compartmentalise the groundwater system. In one instance, data suggest that the character of a regional fault varies along strike length. Other multi-level systems provide information on the vertical component of gradients, both in the area of tailings impoundments and in areas near extensive underground workings. Development of a reasonable hydrogeologic conceptual model from which to assess both current conditions and potential future conditions after re-flood was significantly improved by the availability of multi-level data.

Figure 1 Giant Mine Site Map with Monitoring Locations



1. INTRODUCTION

Development of hydrogeologic conceptual models to estimate the controls on groundwater movement in underground mine sites can be a complex undertaking. Models require incorporation of complex geology as well as mine effects. Without sufficient data to develop a reasonable, defendable, conceptual model, estimates of reflood or future flow conditions may be fatally flawed.

The Giant Mine, located on the outskirts of Yellowknife, NWT operated for over 50 years, producing over 7 million ounces of gold and approximately 265,000 tonnes of arsenic trioxide dust as waste from the ore refining process. Arsenic dust was stored in 15 relatively shallow underground chambers under the assumption that permafrost, which existed in the mine area during the early stages of development, would re-establish upon cessation of mining operations and act to protect the dust from transport in the groundwater system. As it turns out, the permafrost is degraded to the point where it is unlikely to refreeze naturally, and so the arsenic may leach into the groundwater system and, subsequently, into the environment if the mine were allowed to flood under the current conditions.

A closure plan for the Giant Mine is currently being prepared by Indian and Northern Affairs Canada (*http://nwt-tno.inac-ainc.gc.ca/giant/index_e.html*). This plan will incorporate active freezing of the arsenic storage chambers as a long-term containment methodology. An understanding of the site hydrogeology, particularly the effects of major structural features, is an integral component for assessing potential re-flood conditions. As the mine is currently only flooded at lower levels, developing a strong understanding of controlling features is a difficult, but important, component of the closure planning process.

This paper presents data from a multi-level monitoring system at the site that was designed to provide information on certain major structures and the effects of mine workings on the hydrogeological system.

BACKGROUND

1.1 Geology

The Giant mine is situated within the Yellowknife Greenstone Belt (YGB), in the Slave Province. The YGB consists of a NE striking, steeply SE dipping homocline of mafic metavolcanic and intrusive rocks of the Kam group (2.72-2.70 Ga), structurally overlain by NE striking intermediate and felsic metavolcanics of the Banting group (2.66 Ga) (Lewis, 1985).

The Kam Group is subdivided into four formations: a lower mafic dyke complex (Chan Fm.); a sequence of massive and pillowed metabasaltic flows, interlayered with cherts and felsic tuffs (Crestaurum Fm.); rhyodacite breccias interbedded with felsic tuffs and pillowed dacites (Townsite Fm.); and massive and pillowed metabasaltic flows, pillow breccias and interflow sediments (Yellowknife Bay Fm.). The Giant mine is situated in the Yellowknife Bay Fm. and Townsite Fm.

The mine site is bound by a series of major Proterozoic faults (West Bay, Townsite, Akaitcho, 3-12, and Rudolph). The characteristic of each fault zone varies along strike and down dip. Figure 1 shows the general layout of the Giant Mine and major structures.

The West Bay fault is the major fault in the Yellowknife area, and bounds the Giant mine site to the west and south. It is typified by a discrete, steeply west dipping fault plane (<15 cm wide) that often contains fault gouge and slickenslides. Along strike the West Bay fault widens (up to several metres wide) and hosts barren calcite-quartz-hematite mineralisation. In some areas, the West Bay fault is a 1m thick mineralised zone. In the north, a zone greater than 10 m in width of quartz-hematite cataclasis mineralisation is exposed on surface in the West Bay fault.

The Townsite fault is located to the south-east of the Giant mine site. The Townsite fault, observed underground, and on surface, is typified by a narrow (<5 cm wide), gouge filled, fault plane that appears dry.

The Akaitcho fault bounds the Giant mine site to the north-east. On surface the Akaitcho fault is a narrow (<10 cm wide) gouge filled, slickenslided, fault plane. Intersection with the Akaitcho fault during drilling or tunnelling has produced no reported inflow.

Where observed, the Rudolph and 3-12 faults are very narrow structures, typically less than 5 centimeters wide, but up to 10 centimeters in places. They may contain central quartz veins, and commonly comprise sets of narrower splays, which bifurcate from the main faults at low to moderate angles

The most recent structural investigation was completed by SRK Consulting in 2000 with the specific goal of characterising fault and fracture patterns and parameters for integration with the hydrogeologic conceptual model (SRK, 2001). Investigators combined available geologic data with results of a underground reconnaisance study to define 1st, 2nd and 3rd order structures, listed in order of decreasing strike length: 1st order structures are 100's of meters to kilometers in length; 2nd order structures are continuous for 10's of meters or less, and occur as faults and fractures, at a variety of orientations, with regular or irregular spacings. Many of the 2nd order structures may be related to the 1st order structures, possibly as splays or less well-developed products of the same deformation, but their variability suggests that they comprise several generations of faulting; 3rd order structures are continuous for less than 20 meters and occur as regularly-spaced structures that are repeated on a centimeter to meter scale. These structures include joints and fractures, which, in rare cases, have accommodated small amounts (<5 cm) of slip. The West Bay, Townsite and Akaitcho Faults are 1st order structures. The Rudolph and 3-12 Faults are 2nd order structures. Numerous 3rd order structures were observed and documented.

The structural framework defined by the Proterozoic fault system around the Giant Mine consists of a broad interconnected network of major structures, separating discrete domains of minor structures. Each domain is characterized by a unique orientation distribution of dominant fault sets and coincides, to some extent, with sharp changes in the dominant rock types. These observations allowed definition of 11 distinct 'lithostructural' domains. The boundaries of the domains coincide with major structural and/or lithological breaks.

1.2 Mine Layout and Geometry

The general mine layout, shown on Figure 1, follows the dominant north-south trending shear zone. The tunnel system can be seen in Figure 1 to be elongated along this trend, and is expected to act as an extended "envelop" with respect to intercepting and altering groundwater flow paths in the mine area.

The mine tunnel system includes 11 main levels, extending to approximately 1228 meters depth (2000 feet). Mine levels are named by the average depth at the central "C-shaft" (eg. 2000 Level is at 1228 meters). Vertically, the mined volume extends along the axis of the mine fairly uniformly in the south and central area. This changes in the northern section, where the tunnels do not extend below the 1500 Ft Level (~460m depth) and to the south of "C" Shaft where the mine only extends to the 700 Level (~200m depth). A small section of the 2000 Level extends eastward under Yellowknife Bay.

The combined length of mine workings is estimated to be on the order of 80 kilometers.

1.3 Groundwater

Historically, water level and hydraulic conducitivity data at the Giant Mine has been minimal to non-existent. Mine geologists recorded many instances of groundwater inflow into the mine when they mapped the drifts on the main levels of the mine. Groundwater inflow was noted to occur along faults, joints and fractures, but rarely along the contacts of intrusive bodies. Water flow through faults and joints is irregular, making predictions of flow rates through specific structures difficult, if not impossible Conceptualisation of groundwater flow under current and future re-flood conditions was limited to similar conditions observed at other underground mines (SRK, 2002).

Pre-mining groundwater flow in the vicinity of the Giant Mine was likely dominated by the relatively flat surface topography and the locations of streams and lakes in the area of the mine. The mine currently acts as a hydraulic sink. All flow lines passing through the area affected by the mine are either captured within, or deflected by, the drawdown cone that is created by dewatering of the mine. Geochemical evidence suggests that water also flows from Great Slave Lake into the mine workings. Following reflood of the mine workings, groundwater can be expected to again flow towards Great Slave Lake. However, flow lines will be modified from the original pathways by interaction with the flooded tunnels.

A water balance was constructed for the mine area. Based on mine dewatering data, it was estimated that approximately 1940 m3/day of water are pumped under normal conditions. Of this, approximately 57%, or 1100 m3/day, is lateral groundwater inflow (SRK, 2005a).

As part of the planning for groundwater data collection, a series of meetings were held with a "Hydrogeology Experts Group" developed for closure planning. Based on available structural and hydrogeologic information, it was recognised that characterisation of every structure was not achievable. It was determined that a monitoring system should target large scale structures considered important to groundwater flow (ie. 1st and 2nd order structures) and having potential to affect re-flood conditions. Additionally, the monitoring system was designed to allow collection of background water level and water quality information to act as a base for long-term monitoring.

2. MULTI-LEVEL MONITORING SYSTEM

A series of 14 multilevel monitoring wells was installed across the site during field programs in 2001 and 2004. Locations of the monitoring systems are shown on Figure 1.

Multi level systems were installed in available exploration drillholes where accessible, open and in locations deemed useful. Dedicated drillholes were completed for specific large scale strucutures and to fill in "holes" in the monitoring system network. Drillholes were also targeted in each of the fracture domains determined by structural studies.

Existing exploration drillholes were re-logged for hydrogeologic purposes and developed using surge blocks suspended by a drill and/or standard flushing to remove rod grease. Dedicated drillholes were drilled with water, logged on site for geotechnical and hydrogeological properties and developed to remove drill cuttings. Packer testing was conducted at certain intervals to provide information regarding hydraulic conductivity.

Multi-level systems at the Giant Mine utilised the Westbay© system, which allows isolation of monitoring zones using hydraulically-inflated packers. Zones can be located at virtually any position in the drillhole and have variable lengths. Pressure monitoring and water sampling in each zone is conducted using a wireline tool that can be positioned at each monitoring point. Monitoring points in each zone are designed to hydraulically isolate the external zone from the internal working area. Water levels in the PVC working zone are kept relatively low compared to natural water levels to ensure that monitoring zones are not contaminated by water inside the PVC. Multi-level systems were designed on-site allowing zone definitions based on observed geologic and hydrogeologic properties.

Of the 14 multi-level systems, five were targeted specifically at major structural features. Eight of the monitoring systems, including one of the fault-specific systems, were installed in existing exploration drillholes.

Fault-specific monitoring systems targeted four major structural features: the West Bay Fault, the Townsite Fault, the Rudolph Fault and the Akaitcho Fault. These structures are shown on Figure 1.

The remaining 9 monitoring systems were distributed to provide general coverage of the mine area, including the different lithostructural domains identified during structural mapping.

3. RESULTS

3.1 Fault Data

Figures 2 – 7 present piezometric data from fault-specific monitoring systems. With the exception of S-Diand-021, piezometric data is from June 2005. S-Diand-021 is believed to have been vandalised soon after installation and is now blocked. Piezometric data for this hole is from September 2004, approximately 1.5 months after installation.

Pressure transducer depths are indicated on each log, as well as packer positions. Geology is shown graphically along the "Vertical Depth" axis. The following key corresponds to geology on all figures.

Mafic flow, Mafic indeterminate or chlorite schist

Pillow Flow — Pillow Breccia

Meta-gabbro — Diabase

Meta-sediments — Granitics

Breccia — Fault Zone

Major Fault — Minor Fault

Major structures in each drillhole are indicated by heavy dashed lines. Lines are extended horizonally from position on drillhole to geology and vertically for comparison with piezometric data only; inclination is not necessarily vertical or horizontal. Where appropriate, the side of individual structures on which the mine workings are located are indicated.

Figure 2 1857 West Bay Fault

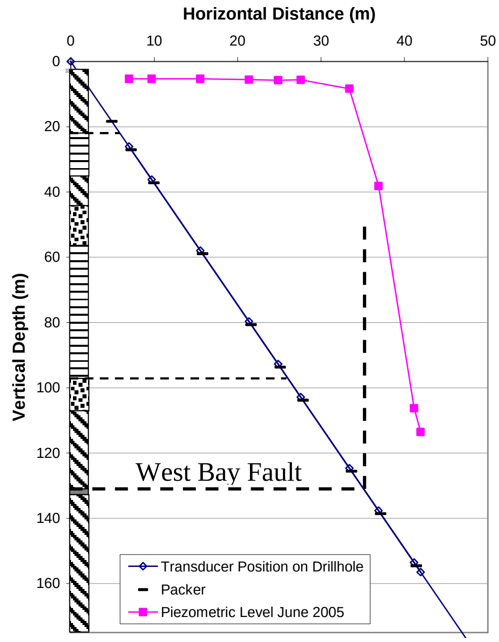


Figure 3 S-Diand-021 West Bay Fault

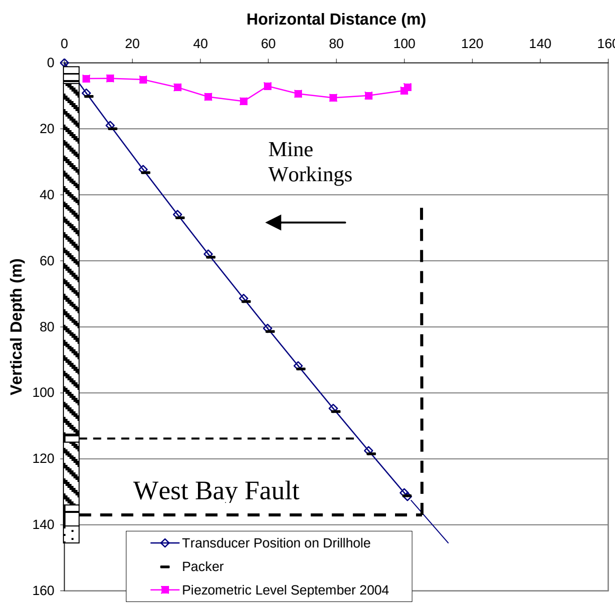


Figure 4 S-Diand-001 Townsite Fault

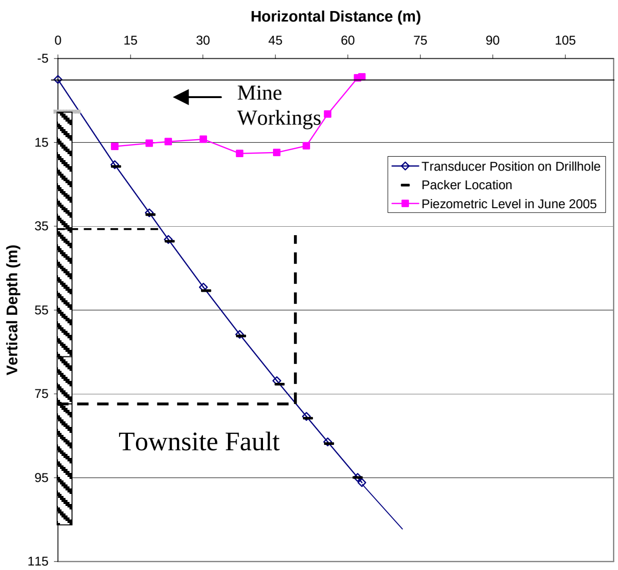


Figure 6 S-Diand-002 Rudolph Fault

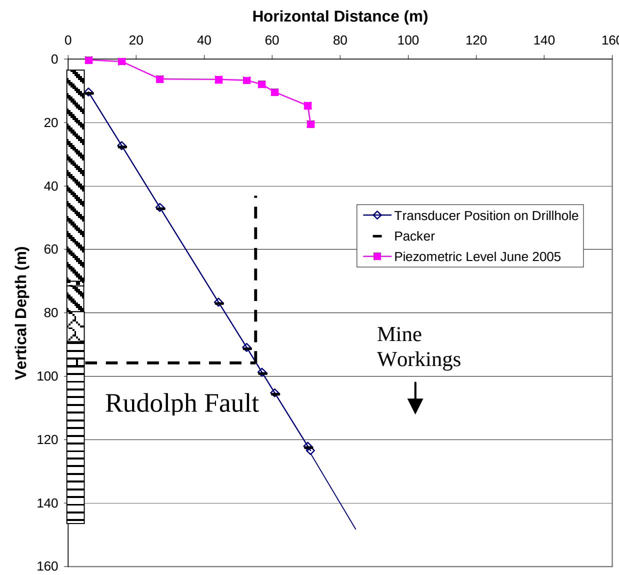


Figure 5 S-Diand-022 Akaitcho Fault

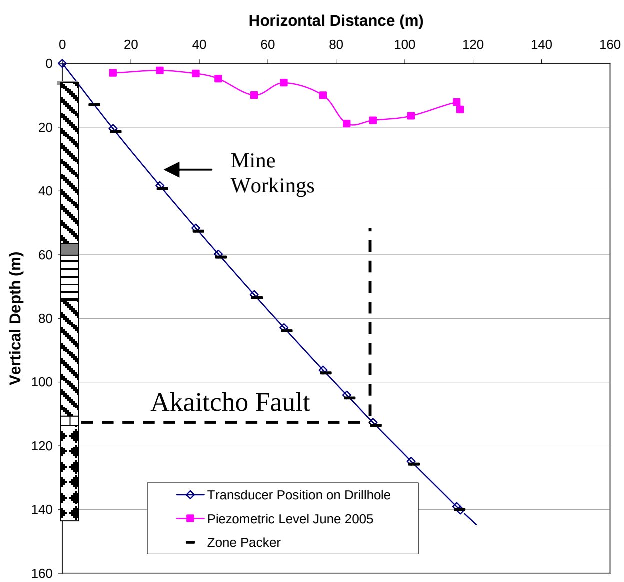
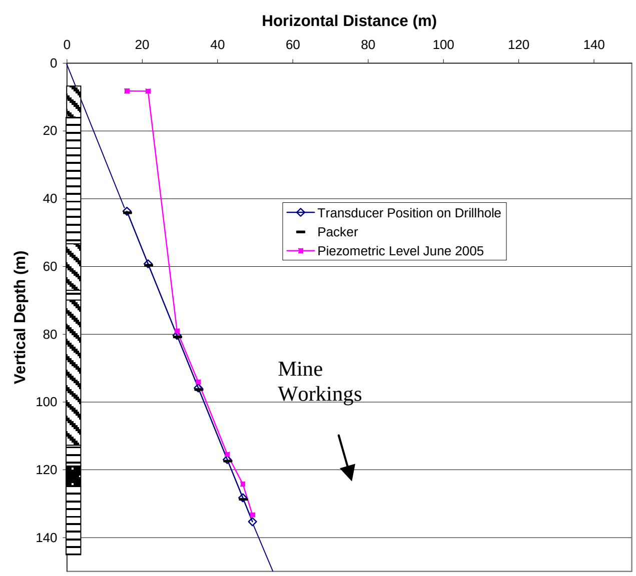


Figure 7 S-1955 Influence of Mine Workings



Piezometric data at these monitoring locations indicates that faults in the Giant Mine area can have variable influence on groundwater flow directions, both between individual structures and, likely, along structures.

Data from the West Bay fault (Figures 2 and 3) indicate that the fault may act as a significant barrier to flow in certain areas, while in others may have no significant visible effect.

In S-1857, the mine side of the fault has water levels significantly lower than on the non-mine side.

This fault, which is oriented roughly perpendicular to the regional flow direction in this area, acts as a barrier to flow. Mine dewatering is interpreted to have caused a head drop across the fault on the order of 100 meters in less than 10 meters horizontal distance. This suggests that the West Bay Fault has a very low hydraulic conductivity in this area.

S-1857 was originally drilled as an exploration drillhole with a total drilled length of over 1000 meters. Deeper sections of this drillhole likely intersect areas around the mine workings that have been significantly affected by mine dewatering, possibly allowing the drillhole to "drain" to the mine itself.

At S-Diand-021, data presents a significantly different picture, though it is complicated slightly by positioning of monitoring points in relation to the fault: no monitoring points are located on the non-mine side of the fault at this location. Additionally, this location is more than twice the distance from mine workings as is S-1857, though still less than 1000 meters. These results allow several interpretations: that the fault has minimal influence on groundwater flow in this area or, that the influence of dewatering has not reached to this distance in this area.

Data from the Townsite Fault monitoring location shows different effects of mine dewatering (Figure 4). The monitoring location is approximately 300 meters from the nearest mine workings, similar to that of S-1857, yet there is minimal drop in the piezometric level. Data on the side of the fault further from mine workings indicates a significant drop in piezometric level, but most of the drop is before the fault, not across it. A slight drop in piezometric level can be seen across the fault and on the side of the fault closest to mine workings, but it continues for numerous monitoring zones away from the fault. Initial review of the data suggests that the immediate area on the mine side of the fault may be acting to drain surrounding rock, possibly a result of higher fracture intenisity in this area that could be a larger scale result of the fault itself.

Incorporation of topography with this data presents an alternate interpretation. Deeper zones of the monitoring system extend into an area of higher ground elevation relative to shallow portions of the drillhole. In this area, piezometric levels may be controlled more by topography and, to a lesser extent, by variations in hydraulic conducitivity. In general, the Townsite Fault in this area is interpreted to have minimal influence on groundwater flow. This is supported by observations of the fault where it intersects underground workings. The fault generally appears dry with only minor wet patches. If a highly conductive structure, one would expect it, or the area around it, to act as a conduit between Great Slave Lake and the mine workings.

The Akaitcho Fault (Figure 5) acts similarly to the Townsite Fault. Prior to June 2005, data indicated that the fault monitoring zone had the lowest piezometric levels. June 2005 data suggest the next zone in, on the mine side, has the lowest levels. These data suggest that the Akaitcho Fault, or possible highly fractured rock adjacent to the fault, could act as a groundwater conduit. Observations in mine workings that intersect the fault, located on the order of 400 to 500 meters to the northwest, indicated that the fault is dry in that area.

The monitoring system for the Rudolph Fault is located relatively close to the mine workings compared to other systems. Data for this system, S-Diand-002, is shown on Figure 6. Piezometric levels are all relatively close to ground surface, though a downwards hydraulic gradient is observed, increasing slightly across the fault. These data suggest that the fault may act as a minor barrier in this area.

3.2 Effects of Mine Workings

Data from many of the fault-specific monitoring systems suggest, as expected, that the mine workings impart a significant control on hydraulic gradients. The monitoring system in S-1955, an exploration drillhole collared relatively close to Great Slave Lake that extends towards the mine workings, provides data from an area not interpreted to be affected by a major structure (Figure 7).

The data from S-1955 indicate that bedrock encompassed in the lower 5 monitoring zones is likely draining towards the mine workings. For 6 to 7 months after installation, piezometric levels in the deepest monitoring zones were below the elevation of the monitoring ports and were basically dry, potentially indicative of a drainage effect. Since that time, pressure data in these zones have shown an increase equivalent to only a few meters of head, suggesting the monitoring zones have not filled with water. This is significantly different from shallow monitoring zones, which show piezometric levels close to ground surface. These data suggest that the drillhole itself may be acting as an efficient drain towards the mine workings and that hydraulic conductivity may change rapidly with depth.

4. DISCUSSION

From a closure planning perspective, one of the most significant issues for stakeholders and the public has been the potential for either unexpectedly rapid mine reflood or direct connection between the mine workings and Great Slave Lake. Available data suggest that a direct connection is not likely. While both structural and hydraulic monitoring data do indicate that fault character likely changes along strike length, there have been no data or observations of major inflow from these structures. The majority of data suggests that most of the faults act as barriers, not conduits. The only fault that could be suggested to have conduit properties is the Akaitcho Fault, but hydraulics in the vicinity of this structure, as well as the Townsite Fault, may be more affected by an adjacent "damage zone". Characterisation of this potential damage zone is not currently possible.

Detailed logging of the drill core from S-Diand-001, which intersects the Townsite Fault, does not indicate a significant increase in fracture density in the potential damage zone area. For S-Diand-022, which intersects the Akaitcho Fault, logging did indicate an increase in joint density towards the fault. As is often the case in studies of this type, different types of observations and data are somewhat inconsistent.
Despite the presence of inconsistencies, the use of multi-level piezometric data has provided important insight into geologic controls on groundwater movement:

- Lithology does not have a consistent effect on piezometric levels, suggesting variability in hydraulic conductivity of any given lithologic type;
- Faults in the mine area are dominantly barriers to flow or exert only minor influence on groundwater flow, at least in the area of monitoring systems;
- Damage zones adjacent to faults may have greater influence on groundwater flow than specific fault structures themselves;
- Shallow bedrock, even in areas thought to be dewatered, may contain perched groundwater, suggesting significant vertical hydraulic conductivity variation;
- The mine tunnel system is the most dominant feature controlling groundwater flow: flow in the mine area is towards the mine workings.

The sum of these results has been important in supporting engineering planning for mine water control systems, both during and after re-flood. If the mine system can be managed as a large-scale drainage structure, mine water levels and, consequently, groundwater flow directions could be controlled. As the mine workings will have hydraulic properties equivalent to hydraulic conductivities 10's to 100's orders of magnitude greater than the bedrock, the mine workings in effect can act as a combined vertical and horizontal pumping well capable of keeping gradients and, subsequently, potential contaminant plumes, oriented towards the mine, from which it can be properly treated and discharged (SRK, 2005b).

Providing confidence that major structures will not act as conduits, or could be controlled if they did, is an important task. Drilling and monitoring results were used to develop "worst-cast" sensitivity analyses for major structures. Numerical modeling results incorporating major structures with significantly greater thickness and hydraulic properties than observed indicate only minor increases in inflow, which can easily be accommodated by conservative mine pump design.

5. CONCLUSIONS

Developing conceptual models for groundwater flow in bedrock systems is a difficult task. Assumptions about the effects of significant structural features can only be supported by appropriate instrumentation and may, in the end, not be significant. The use of multi-level groundwater monitoring systems at the Giant Mine has provided good evidence of the relative unimportance of structures when compared to the effects of the mine workings themselves, and have provided good data for development of engineering systems under mine closure.

6. REFERENCES

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