

# EFFECTS OF PARTIAL FLOODING ON WATER CHEMISTRY FROM THE UNDERGROUND WORKINGS AT THE BRITANNIA MINE

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## ABSTRACT

Although flooding or partial flooding of underground workings at closure is a commonly proposed closure measure, there are a limited number of case studies documenting changes in water chemistry resulting from flooding and cyclic flooding of sulphidic mine wastes.

The Britannia Mine located approximately 50km north of Vancouver, British Columbia operated from 1905 to 1974 producing over 48 million tonnes of copper ore. The mine workings consist of over 80 kilometres of underground tunnels and raises, and five small open pits and glory holes, extending from below sea level to elevations of approximately 1300 metres above sea level. Surface and groundwater entering the mine is contaminated by acid rock drainage from residual sulphide minerals in the mine workings, and emerges from tunnels on the lower levels of the mine. During the conceptual design phase for a Water Treatment Plant for the mine drainage, the mine workings were identified as a possible location for storage and attenuation of peak flows. The volume of the workings available for storage and the changes in chemistry that could occur during flooding were assessed by partially flooding the mine workings and monitoring the flows and drainage chemistry. The workings have since been flooded several times during the investigation and construction phases of the project, and continued monitoring has provided additional insight into the geochemical characteristics of the flooded portion of the workings.

The initial results indicated that flooding leads to a modest reduction in pH, and modest increases in sulphate and metal concentrations in the mine drainage. In the initial flood tests, iron concentrations were most strongly affected, with concentrations increasing from approximately 4 mg/L during flow-through conditions to as high as 78 mg/L in the flooded mine water. Although concentrations increased in response to flooding during subsequent events, the increase has not been as high as indicated by the initial tests, possibly reflecting depletion of oxidation products from the flooded portion of the mine.

## 1. INTRODUCTION

The Britannia Mine, located approximately 50 km north of Vancouver, British Columbia (Figure 1), was operated from 1905 to 1974, producing a total of 48 million tonnes of ore at average grades of 1.1 per cent copper, 0.65 per cent zinc, 6.8 grams per tonne silver, 0.6 grams per tonne gold, and minor quantities of lead and cadmium (BCMEMP 2005). The mine workings consist of over 80 km's of underground tunnels and raises, and five small open pits and glory holes, extending from below sea level to elevations of approximately 1300 metres above sea level, and from the mill at Britannia Beach to the mining core located 4 to 6 km from the mill (Figure 2).

Mining occurred in seven distinct ore zones, all located within strongly deformed and metamorphosed pyroclastic volcanic and sedimentary rocks of the Britannia shear zone. The deposit is classified as a Noranda/Kuroko massive sulphide type, in which sulphide and genetically related deposits of anhydrite, quartz, silicified rock, cherty andesitic sedimentary rocks, bedded chert, and minor barite formed from volcanogenic hydrothermal solutions. Intense regional

metamorphism resulted in partial remobilization and redistribution of the sulphide minerals. The ore occurred primarily as veins, or disseminated and stringer type mineralization, and was invariably associated with quartz.



Figure 1 Location Map

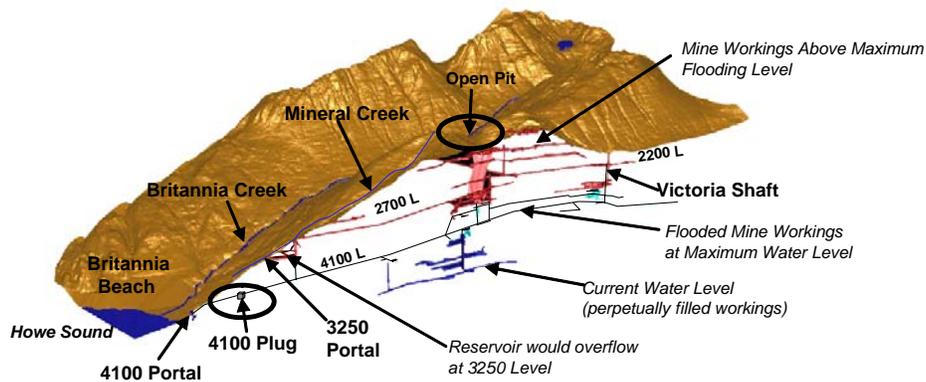


Figure 2 Schematic Cross-section of the Underground Workings

The principal sulphides minerals were pyrite and chalcopyrite, with local concentrations of sphalerite, and minor and erratic occurrences of galena, tennanite, tetrahedrite and pyrrhotite. Non-metallic minerals included quartz, muscovite, chlorite, anhydrite and siderite (BCMEMP 2005).

Surface and groundwater entering the mine is contaminated by acid rock drainage from oxidation of residual sulphides, primarily pyrite, in the mine workings. Low pH's were noticed early in the mine life, with rapid rates of corrosion occurring on everything from pumps and rail lines to the nails on the miner's boots. Historical records dating back to the 1920's indicate copper concentrations reached as high as 2,000 mg/L. The mine water currently has pH's between 3 and 4, with elevated concentrations of aluminum (31 mg/L), cadmium (0.11 mg/L), copper (23 mg/L), iron (4.2 mg/L), manganese (4.3 mg/L), and zinc (23 mg/L) (SRK 2002).

The mine water currently discharges through a haulage tunnel located at the 4100 level (near sea level) which was originally used to transport ore from the core of the mine to the mill at Britannia Beach. A hydraulic plug located 400 metres in from the portal, constructed in 1978, can be used to regulate flow and water levels within the mine workings. The 4100 level workings are connected to a raise and adit located at the 3250 level, 266 metres above the elevation of the plug. This is maximum practical height available for flooding.

In 2001, the B.C. Government began remediation investigations to support construction of a water treatment plant at the site. The plant has been constructed, and started operating in November 2005.

Due to the strong seasonal patterns in flow from the mine, it was considered desirable to use the mine workings as a reservoir to regulate flows to the water treatment plant. It was anticipated that flooding of the

mine workings would lead to increased concentrations due to dissolution of stored oxidation products.

Studies were initiated to predict the chemistry of the flooded mine water, as required to estimate lime consumption rates and sludge volumes in the design of the water treatment plant. A related study was also initiated to assess the storage capacity within the area of the mine workings that could be flooded.

## 2. METHODS

The investigations were completed in two phases.

The first phase involved interpretation of historical flow and chemistry data from the 2200 and 4100 Portals to evaluate annual storage of oxidation products in the workings, and the potential magnitude of effects of seasonal flushing and mineralogical controls on drainage chemistry. Data were analyzed to determine temporal patterns, relationships between flow and chemistry, water level and chemistry, and solubility constraints. Data from the early 1980's was particularly helpful for establishing the effects of flooding on mine water chemistry because water levels were allowed to fluctuate within the mine during that period. Preliminary water quality estimates were made based on the results of this initial data review. However, the range of uncertainty on these estimates was quite large, and a second phase of investigation was required to obtain sufficiently accurate estimates of chemical loading to the water treatment plant.

Access was not possible due to the poor condition of the mine workings, making sampling and testing of materials in the underground workings impractical. In addition, few of the original mine records were available, limiting our ability to define the geometry of the mine workings. A flooding test was therefore proposed to evaluate the storage capacity available within the mine and to assess the condition of the hydraulic plug. This provided a unique opportunity to assess the chemistry of the flooded workings.

Detailed instrumentation was installed at the mine plug to accurately monitor water levels in the mine and outflows. Instrumentation was also installed in the mine catchment to allow more accurate measurements of inflows to the mine (SRK/KC 2002). The mine workings were flooded and the flows and drainage water chemistry were closely monitored.

The first stage of the initial flooding test was completed in 2002, prior to spring freshet, when there would be minimal variations in inflows. From a geochemical perspective, this period also offered the least complication from the effects of flushing in the upper part of the workings. The mine was flooded to a height of 102 metres, with peak levels occurring on about April 25th. About half of the volume flooded was within the haulage tunnel, and the remainder was in raises and stopes in the core of the mine. To minimize the risks of discharge through higher uncontrolled adits, and to ensure the chemistry was within a tolerable range for discharge, the mine was substantially drained prior to freshet. A second stage of flooding was initiated following peak freshet flows. Flooding was then temporarily halted due to more rapid than expected filling of the mine and uncertainties in the remaining void space. Flooding was resumed once inflow rates dropped near the end of freshet, with water levels reaching the peak height of 250 metres on August 16th.

In 2004, the mine workings were flooded again to ensure that the next highest adit (3250 level) could be used as an emergency spillway should the drains in the plug become inoperable for any reason. In 2005 the workings were periodically flooded to restrict flows during rehabilitation of the 4100 level tunnel. Continued monitoring of the chemistry has provided additional insight into the geochemical performance of the flooded portion of the workings.

Water samples were collected either from a location in the 4100 level tunnel, immediately downgradient from the plug that is used to regulate flows, or from a PVC pipe installed to transport the water from the plug to a location just outside the 4100 portal. Water quality was closely monitored during each of the draindown periods. Measurements of pH, specific conductivity, redox, temperature, and copper were taken in the field. The samples were also submitted to a commercial laboratory for analysis of pH, acidity, TDS, TSS, hardness, chloride, fluoride, sulphate, and a full suite of dissolved and total metals by ICP-OES.

The drainage water quality was used to refine the original predictions of water chemistry, and to provide further insight into how these loads would change over time. Potential solubility limitations were evaluated using MINTQA2, a geochemical equilibrium model (Allison et al., 1991).

### 3. RESULTS AND DISCUSSION

#### 3.1 Phase I Data Review

##### 3.1.1 Early Historical Data

In the early 1980's, the mine owners began to use the 4100 plug to regulate flows to launders used to precipitate some of the copper from the mine water. Flow, hydraulic pressure (indicative of flooding levels) and copper concentrations were monitored regularly through this period, and more detailed chemical analyses were completed on a small number of samples by the Waste Management Branch (WMB) of the B.C. Ministry of Water Land and Air Protection. These data were important because they provided an indication of concentrations that could be expected during flooding of the mine.

Every year from 1980 to 1985, two pressure peaks occurred, corresponding to partial flooding of the workings in June and late fall/early winter when inflows are highest (Figure 3a). Copper concentrations showed pronounced peaks coincident with each flooding event, reaching maximum levels of 30 to 35 mg/L as compared to typical values of 15 mg/L. In the early part of the 1980's monitoring record, the pH of the effluent generally decreased from greater than 3.5 to less than 3.5 during or immediately following peaks in flooding (Figure 3b). Later in the monitoring record, pH's were more consistently greater than 3.5, suggesting that repeated flooding could lead to a reduction in the amount of stored oxidation products available for leaching. Concentrations of several other elements, including cadmium, cobalt, manganese, and zinc, were correlated with the peaks in copper concentration. Peak iron concentrations tended to occur immediately following flooding, and were an order-of-magnitude higher (up to 50 mg/L) than concentrations observed during flow through conditions (typically between 5 and 10 mg/L). The mine was abandoned in 1987 by the owners, and monitoring activities temporarily ceased at that time.

##### 3.1.2 Historical Data from 1990 to 2001

Monitoring activities were resumed by various government agencies (primarily B.C. Ministry of Energy and Mines, B.C. Ministry of Water Land and Air Protection, and Environment Canada) starting in the early 1990's. During this period, pressure levels in the mine were not recorded, but it is thought that the drains through the plug were fully open and the workings were not flooded during this period.

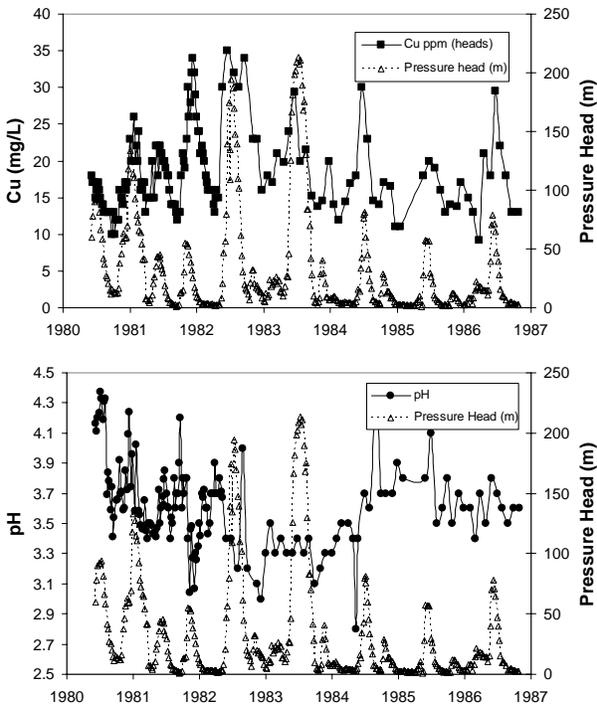


Figure 3 Relationships between a) copper concentrations and pressure head, and b) pH and pressure head in the 4100 Drainage (1980's data)

Results from the 1990's monitoring are summarized in Table 1. During this period, concentrations were reasonably steady, although some seasonal patterns were evident. Figure 4 shows the seasonal relationships in flows and copper concentrations for a period of intense monitoring in 1996. As indicated in the figure, flows started to increase in April and May, reaching a maximum in June. Copper concentrations were generally high in April and May, but reached a minimum in June and July, and then increased in the late summer/early fall when flows were at their minimum. Similar seasonal trends were evident for pH and the other metals. These data indicate that there is a weak inverse relationship between copper and flows at this station, and suggest that stored contaminants present in the workings are well flushed during maximum flow periods.

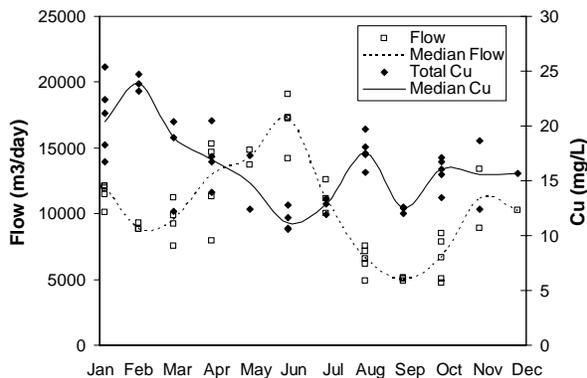


Figure 4 Relationship between flow and copper concentrations (1996 data)

Table 1 Summary of 4100 Drainage Chemistry from the 1990's Monitoring Period

Parameter	Units	Concentration	
		Average	90th Percentile
Flow	m <sup>3</sup> /day	9704	16236
pH	s.u.	3.8	3.3
Acidity	mg CaCO <sub>3</sub> eq/L	234	321
SO <sub>4</sub>	mg/L	1528	1692
Ca	mg/L	391	435
Mg	mg/L	69	80
Al	mg/L	26	33
Cd	mg/L	0.089	0.112
Cu	mg/L	18	22
Fe	mg/L	4.5	7.4
Mn	mg/L	4.2	5.1
Zn	mg/L	21	24

Geochemical modelling completed on selected results from the 1990's data indicated that the 4100 drainage chemistry was close to saturation with respect to gypsum, ferrihydrite, Al(OH)SO<sub>4</sub>, and manganese oxides. However, most trace metals are apparently not limited by equilibrium with secondary minerals based on available thermodynamic data, indicating that concentrations were likely to be controlled by rates of generation and flushing.

### 3.2 2002 to 2005 Monitoring Results

#### 3.2.1 Water Levels

As described previously, there have been three main periods of flooding, including specific flooding tests in 2002 and 2004, and flooding to limit outflows during the construction and initial operations period from August 2005 to present. The water levels associated with each of these periods are presented in Figure 5. In interpreting these results, it is important to note that the 2002 tests were completed following a period of approximately 15 years without deliberate flooding. In contrast, there was only a 2 year gap between the 2002 test and the 2004 test, and then a gap of less than one year before the most recent flooding, during which time the mine was almost continuously flooded. Since 2002, the plug has been operated with a minimum head of at least 20 metres to prevent floating debris (such as rail ties) from interfering with the drains. This may have limited circulation through the workings.

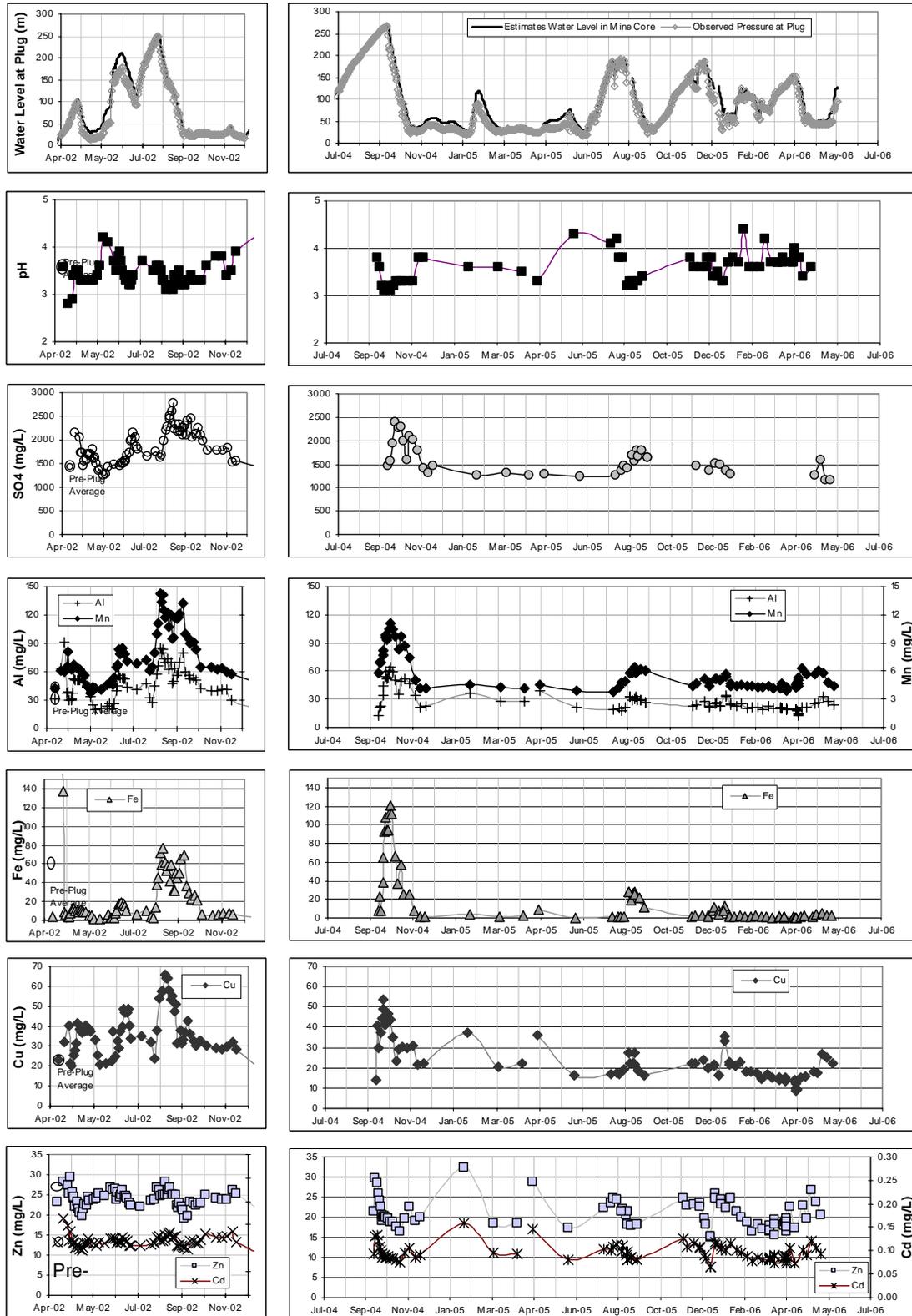


Figure 5 Relationships between water level and chemistry (2002 to 2005): a) water level, b) pH, c) sulphate, d) aluminum and manganese, e) iron, f) copper, g) zinc and cadmium

### 3.2.2 2002 Chemistry

Monitoring data from the 2002 flooding tests (Figure 5) indicated that the pH decreased, and concentrations of most parameters increased approximately two weeks following the peaks in water level. These changes reflected dissolution of stored oxidation products in the workings. Peak concentrations were progressively higher as flooding levels increased, reflecting both an increased amount of stored oxidation products at higher elevations in the mine, and a larger volume of workings.

Other interesting features in the data are summarized as follows:

- Although the pH was lower in the flooded mine water, pH's rarely decreased below 3.3, and only decreased below 3.0 at the very beginning of the initial plug test. This suggests that there is a lower bound on pH in this system, for example buffering caused by dissolution of ferric hydroxide sludges.
- Sulphate concentrations in the third draindown stayed high for several weeks after the flood water had passed out of the mine.
- Copper, aluminum and manganese concentrations were strongly correlated. Three weeks after the final peak in concentrations, all three of these metals exhibited a second peak. This is interpreted as the arrival of drainage held up in fine materials in the mine.
- Concentrations of the above metals decreased much sooner than sulphate.
- Iron showed the most dramatic response to the flooding, with concentrations increasing from a pre-test level of 4 mg/L to a peak of 78 mg/L. This was accompanied by a downwards shift in redox. Equilibrium modelling (discussed below) indicated that the dissolved iron during this period was present primarily as the ferrous form.
- Zinc and cadmium concentrations showed little variation during the test, and appeared to be unaffected by the flooding episodes. Geological reports for the site indicate that zinc occurrences were restricted to certain areas of the mine, and it is therefore possible that there is little zinc sulphide mineralization in the flooded portion of the mine. Cadmium tends to occur in association with zinc in these types of deposits, and could be expected to follow the same pattern.

Equilibrium modelling was completed on a series of samples representing different periods of the 2002 plug tests. As mentioned above, the iron speciation calculated in MINTEQA2 shifted from ferric ( $\text{Fe}^{3+}$ ) dominated to ferrous ( $\text{Fe}^{2+}$ ) dominated during the final peak in the flooding test. This may have been due to longer holding times during this test. Saturation indices for the aluminum minerals and gypsum were close to saturation, and were highest during the final peak in concentrations, indicating minimum dilution by clean water during this phase of the test. Ferrihydrite was

undersaturated in all of the plug test samples, but was close to equilibrium in the final post draindown sample. Other parameters were well below saturation, indicating concentrations were probably not limited by secondary mineral controls.

### 3.2.3 2004 and 2005 Chemistry

Data from the 2004 Flood Test (Figure 5) showed very similar results to those from the 2002 test, with a decrease in pH, and increase in sulphate and metal concentrations.

In contrast, data from flooding events in 2005 (Figure 5) showed only a slight response to flooding, with minor and short-lived decrease in pH and only slight increases in sulphate and metal concentrations. These changes may reflect the relatively short period of time the workings were exposed to oxidizing conditions following the 2004 test, the lower water levels, or the nearly continuous state of flooding during the 2005 construction period. It is also possible that repeated flooding has reduced the amount of oxidation products available for leaching within the flooded zone of the mine or that reduced circulation in the 4100 tunnel has reduced the rate of oxidation in this part of the mine.

## 4. SUMMARY AND CONCLUSIONS

Monitoring data from 2002 to 2005 provide a clear indication of the changes in chemistry resulting from repeated flooding of the Britannia Mine workings during the investigation and construction stages associated with developing a water treatment plant at the site.

Flooding resulted in lower pH conditions and increased sulphate and metal concentrations in the drainage water, indicating some accumulation of stored oxidation products occurred in the area of the mine that was subjected to flooding. However, the magnitude of the increase was modest in comparison to other flooded mines in the literature (Aljoe 1994, Donovan et al. 1991, Iversen et al., 2000, Perry 2001), possibly due to the high rates of precipitation at this coastal location.

The results are consistent with the historical data, which showed a weak inverse relationship between chemistry and flow, with lower concentrations occurring during periods of maximum inflow, indicating that concentrations of most parameters were limited by rates of sulphide oxidation and flushing rates, rather than equilibrium with secondary minerals.

## 5. ACKNOWLEDGEMENTS

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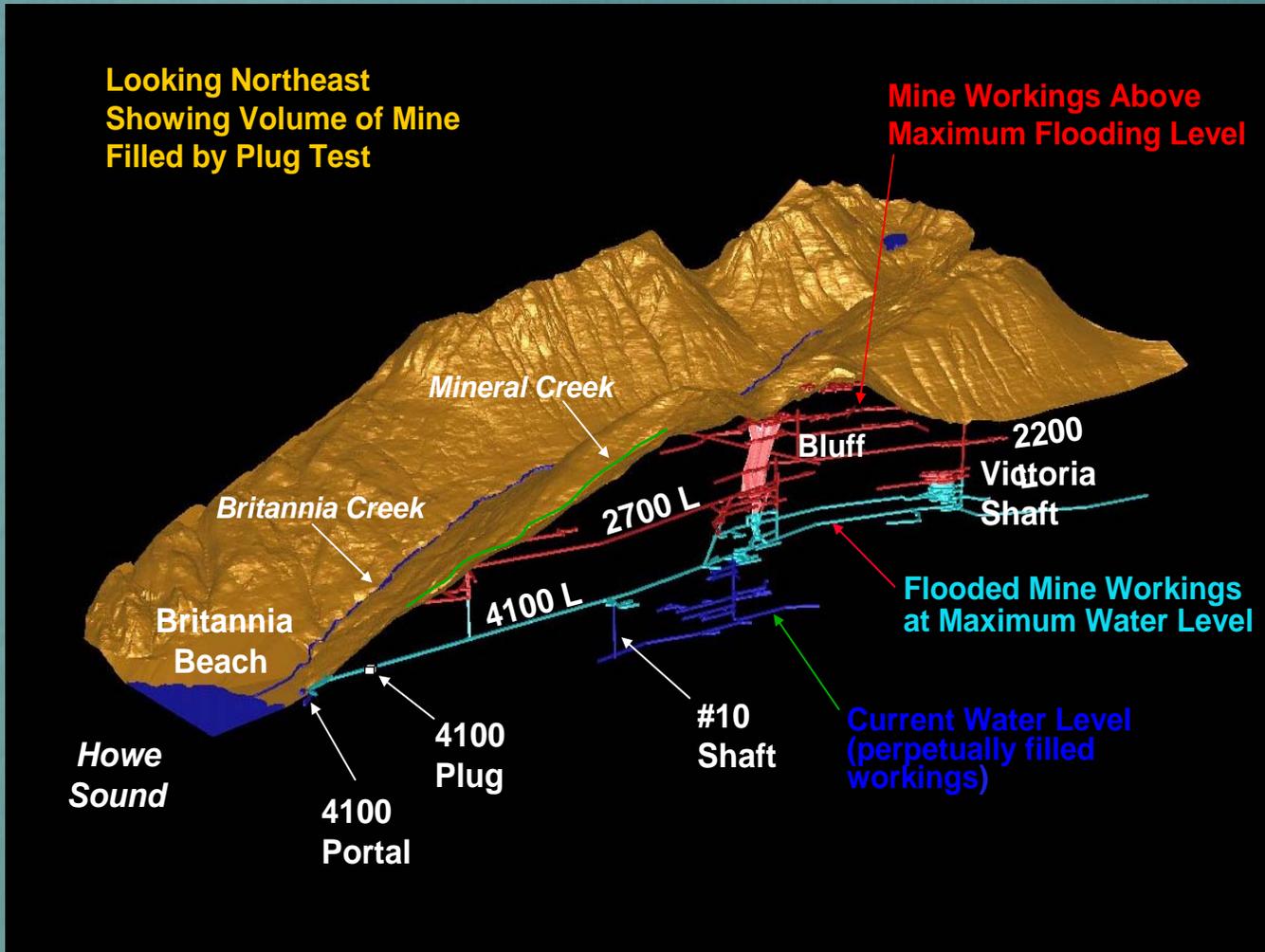
# Effects of Partial Flooding on Water Chemistry from the Underground Workings at the Britannia Mine

*Presented by: Kelly Sexsmith*

# Location



# Mine Workings





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