Evolution of Water Quality in the Goathill North Rock Pile at the Questa Mine and the Impacts on Under Drain Performance

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Abstract

Some of the groundwater beneath Chevron Mining Inc.'s Questa Mine in northern New Mexico seeps through mineralized bedrock, the toe of the Goathill North mine-overburden rock pile, and then through drain rock located at the base of the rock pile. Rainwater and snow melt infiltrate, flow past, and partially dissolve minerals such as pyrite, calcite, chlorite, and fluorite, producing distinct geochemical signatures for each flow zone. In the low permeability, saturated bedrock, a low flux of oxygen reaches pyrite, and calcite buffers the pH, limiting acid rock drainage. In contrast, the Goathill North rock pile consists of unsaturated, granular material with high permeability and porosity. Air advecting through the rock pile oxidizes pyrite at higher rates than occurs in the bedrock. Water chemistry at the toe of the Goathill North rock pile indicates that buffering capacity has been consumed and shows increased concentrations of total dissolved solids and most metals between the bedrock water and rock pile water. Iron and potassium concentrations decrease, and sulfate and calcium concentrations remain constant. Precipitation of goethite, jarosite, and gypsum occurs in the rock pile material and, particularly, in the drain rock, where the secondary minerals have reduced the drain flow capacity.

Key Words: Geochemistry, secondary minerals, regrade seep

Introduction

Pyrite oxidation occurs as some of the groundwater beneath Chevron Mining Inc.'s Questa Mine in northern New Mexico seeps through mineralized bedrock, the toe of the Goathill North mine-overburden rock pile, and then through drain rock located at the base of the rock pile. Air advecting through the rock pile oxidizes pyrite at higher rates than occurs in the bedrock, and water quality results indicate distinct geochemical signatures for each of the flow zones. The mineralized water contacts readily available oxygen near the outlet of the rock drain causing precipitation of goethite, jarosite, and gypsum. These secondary minerals have reduced the drain flow capacity and caused seep migration. This paper discusses water quality results from the Goathill North rock pile and how these results confirm expected changes in water quality through contact with these minerals.

Project Location

The Questa Mine is located in northern New Mexico on the western slope of the Sangre de Cristo Mountains in Taos County, New Mexico. The mine property is located approximately 5.6 km (3.5 mi) east of the Village of Questa and 8 km (5 mi) west of the Town of Red River along the Red River (Figure 1). The Sangre de Cristo Mountain Range is comprised of rugged terrain with peaks reaching over 4,300 m (14,000 ft) elevation with vertical reliefs of more than 1,600 m (5,200 ft). The Questa Mine elevations range from 2,400 m (7,900 ft) to 3,260 m (10,700 ft).

Rock Pile Summary

Molybdenum was mined in the Questa Mine area from 1919 to 1958 by a variety of conventional underground mining methods. The Questa Mine operated as an open pit mine from 1965 and to 1983. Underground mining operations started in 1981 and continue today. Waste rock from the open pit and from underground mine development was dumped into a series of piles surrounding the open pit. The rock piles are characterized as blasted volcanic rock comprised of sandy gravel and gravelly sand. Each rock pile was developed by end-dumping the material so the slope on the edge of each rock pile was at its angle of repose. The Goathill North and Sugar Shack West rock piles have since been regraded to reduce the rock pile slope angles. The mine property covers approximately 1600 ha (4000 ac) and includes the open pit, 10 waste rock piles, underground mine workings, and mill. The open pit and rock pile locations are shown on Figure 1.

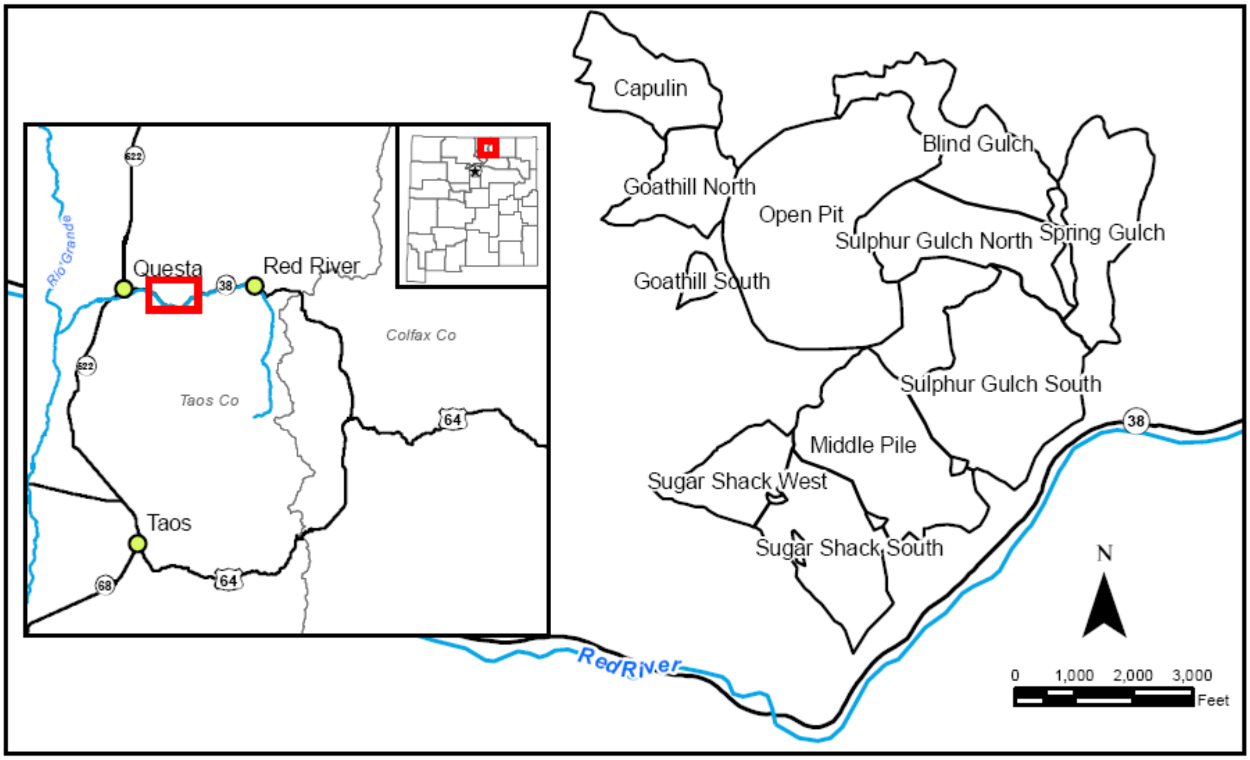

Figure 1. Location Map of the Questa Mine

The rock pile material consists of mixed volcanic rocks that have been blasted, excavated, hauled, and end-dumped. The dumping process caused a natural sorting of the materials with the upper portion of the rock pile tending to contain the fine-grained material and the toe of the rock pile tending to contain coarse rock rubble. The progression of the dumps caused localized layering that is roughly parallel between each layer and the rock pile face at the 36º rock pile angle of repose (McLemore, 2009a). The rock piles are heterogeneous and each layer contains a mixture of the rock types depending on the geologic units that were being mined at that time.

Goathill North Rock Pile Summary

The Goathill North rock pile is located west of the open pit at the headwaters of the Goathill Gulch drainage. It consists of approximately 4.2 million m^3 (5.5 million yd^3) of material that was excavated from the open pit and placed at the headwaters of Goathill Gulch between 1964 and 1974. The rock pile is approximately 180 m (600 ft) in height and covers an area of approximately 20 ha (50 ac). Figure 2 shows the rock pile and surrounding area.

Goathill North Rock Pile was constructed in an area characterized by hydrothermal alteration scars, zones where Quart-Sericite-Pyrite altered rock were exposed near the surface and subject to weathering for thousands to hundreds of thousands of years. The rock pile covers much of the alteration scar, but the alteration scar forms the escarpment along the southern boundary of the rock pile. The toe of the pile was founded on a colluvium bench underlain by pre-sheared material. This bench was the remnant of a natural historic landslide. Pre-mine photos show evidence of historical sliding activity in the same area (Norwest 2004a). Foundation movement associated with the initial development of the slide occurred between 1969 and 1973, and continued to occur for more than 30 years until the rock pile was regraded.

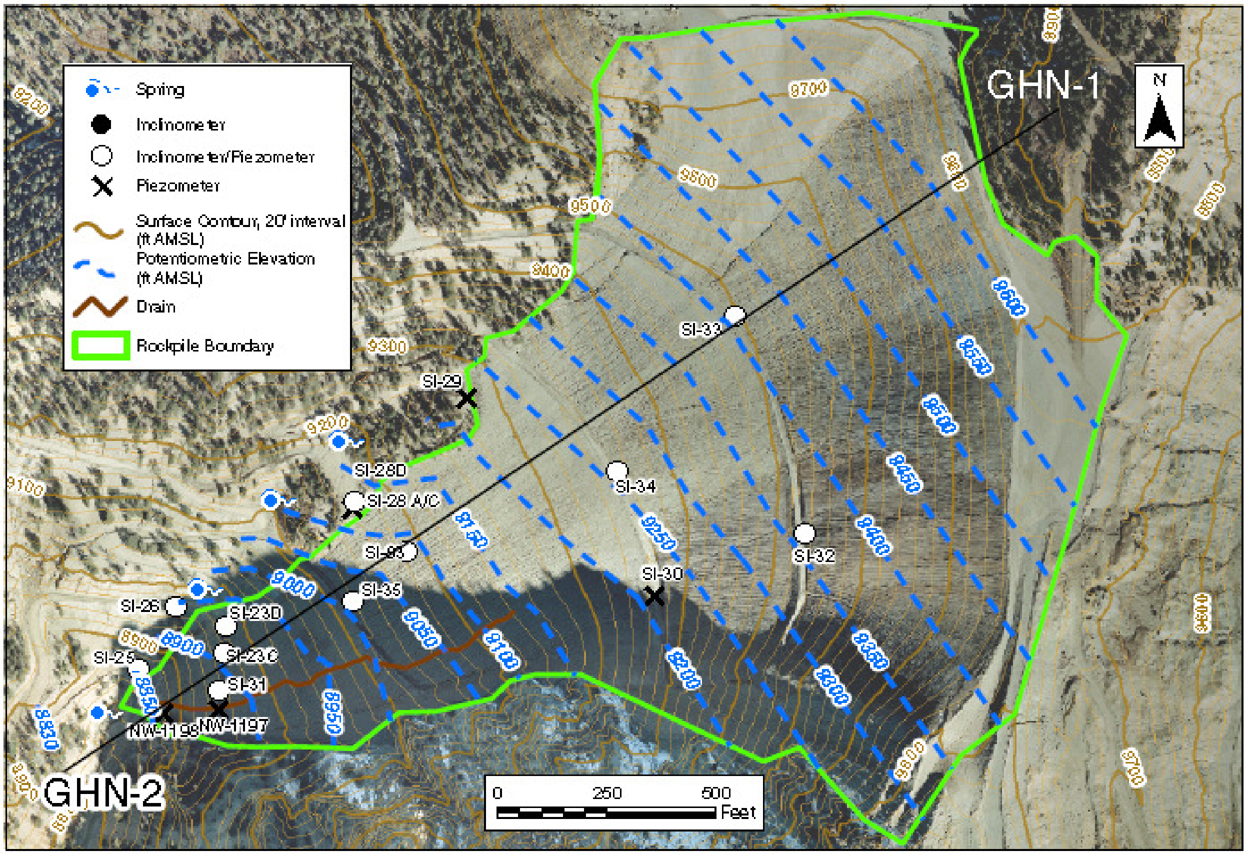

Figure 2. Goathill North Rock Pile (After Regrade) with Current Potentiometric Surface

A field investigation was executed to investigate the cause of the landslide and its extent (Norwest 2004a). The investigation included pre-mining and post failure information, bedrock geology and hydrology, and geotechnical properties of the associated rocks and slide. Weak foundation conditions associated with pre-shearing were attributed to high bedrock pyrite contents which produce acid drainage and alteration minerals that are more susceptible to weathering. In addition, there is a shallow water table in the weathered zone at Goathill North which contributes pore pressures to trigger slide movements. The seepage also acts as the solution for chemical weathering and the medium for transporting away any dissolved components of the weathered rock. This information was used as the design basis for mitigation of the rock pile (Norwest 2004b). The objective of the mitigation was to control ongoing foundation sliding movements and other foundation shearing mechanisms. Mitigation efforts of the Goathill North rock pile occurred between 2003 and 2006 consisting of a slide investigation and evaluation (Norwest 2004a and 2004b), subsequent regrading, and ongoing monitoring. A rock drain was placed beneath the regraded rock pile to convey seepage water to the toe of the rock pile and to prevent pore water pressure buildup. The drain discharges to a weir used to measure flows from the drain.

Conceptual Geologic Model

The Sangre de Cristo Mountains are part of the Southern Rocky Mountains physiographic province. The western edge of the Taos Range portion of the Sangre de Cristo Mountains lies approximately two miles west of the mine and defines the easternmost edge of the Rio Grande rift valley.

Intrusive emplacement within the volcanic sequence fractured the country rocks. These fractures can act as fluid conduits for circulating and cooling hydrothermal fluids associated with the sulphide mineralization and hydrothermal processes. At the Questa Mine, high pyrite contents are commonly associated with quartz-sericite-pyrite (QSP) secondary mineral assemblages. Propyllitic alteration during the hydrothermal activity also deposited fluorite, calcite, and chlorite. (McLemore, 2009c)

The Questa molybdenite (MoS_2) deposit is a porphyry molybdenum deposit formed about 25 million years ago during a period of extensive volcanic activity. As the magma intruded into the Precambrian granite and crystallized, molybdenite (along with other minerals) precipitated from the post-magmatic hydrothermal fluid formed by convection of meteoric in origin waters through the volcanic and intrusive complexes to fill fractures and form the veins and breccia matrix that define the Questa Mine orebodies. These orebodies are included within much more widespread zones of pyrite along of Red River valley.

Overlying this pyrite zone is a zone of weathered rock which extends along the Red River valley. This zone is up to 1000 m (3000 ft) wide. Steep cliffs, barren of vegetation, define areas of active mass wastage, and they are representative of acid rock weathering. These weathering and erosion processes create alteration scars – the yellowish-orange colored, craggy cliffs found along the Red River valley and along the southern edge of the Goathill North rock pile (Norwest, 2005).

The geology in the vicinity of the Goathill North rock pile consists of Tertiary aged volcanic rocks, particularly the Amalia Tuff (Trt), andesite porphyry flows (Tan), and quartz latite porphyry flows (Tql). The Amalia Tuff is a welded, ash flow deposit that is gray to reddish brown with a rhyolitic composition. The andesite and quartz latite are fine-grained and pophyritic. They occur in flows up to 60 m (200 ft) thick and as dikes and sills (McLemore, 2009c). Their locations are shown on Figure 3. A cross-section running east to west is included as Figure 4.

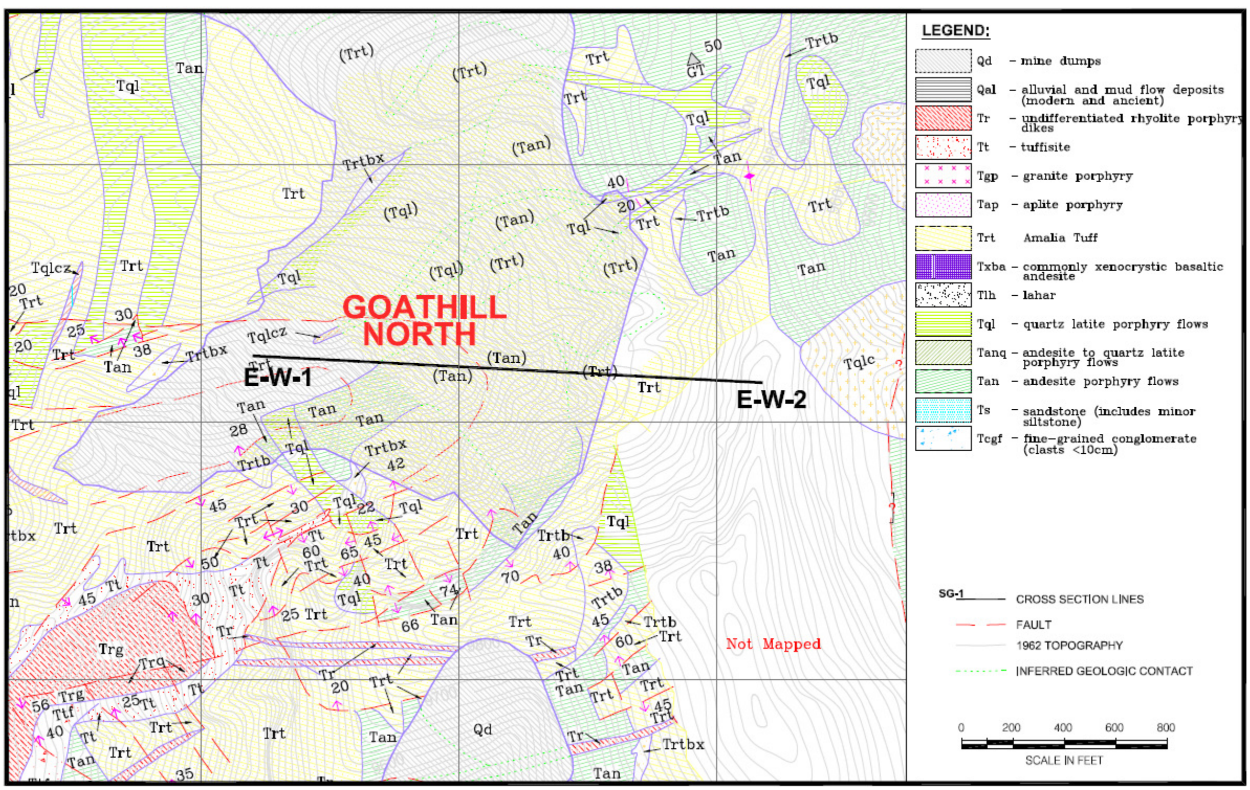

Figure 3. Geologic Map of Goathill North Area

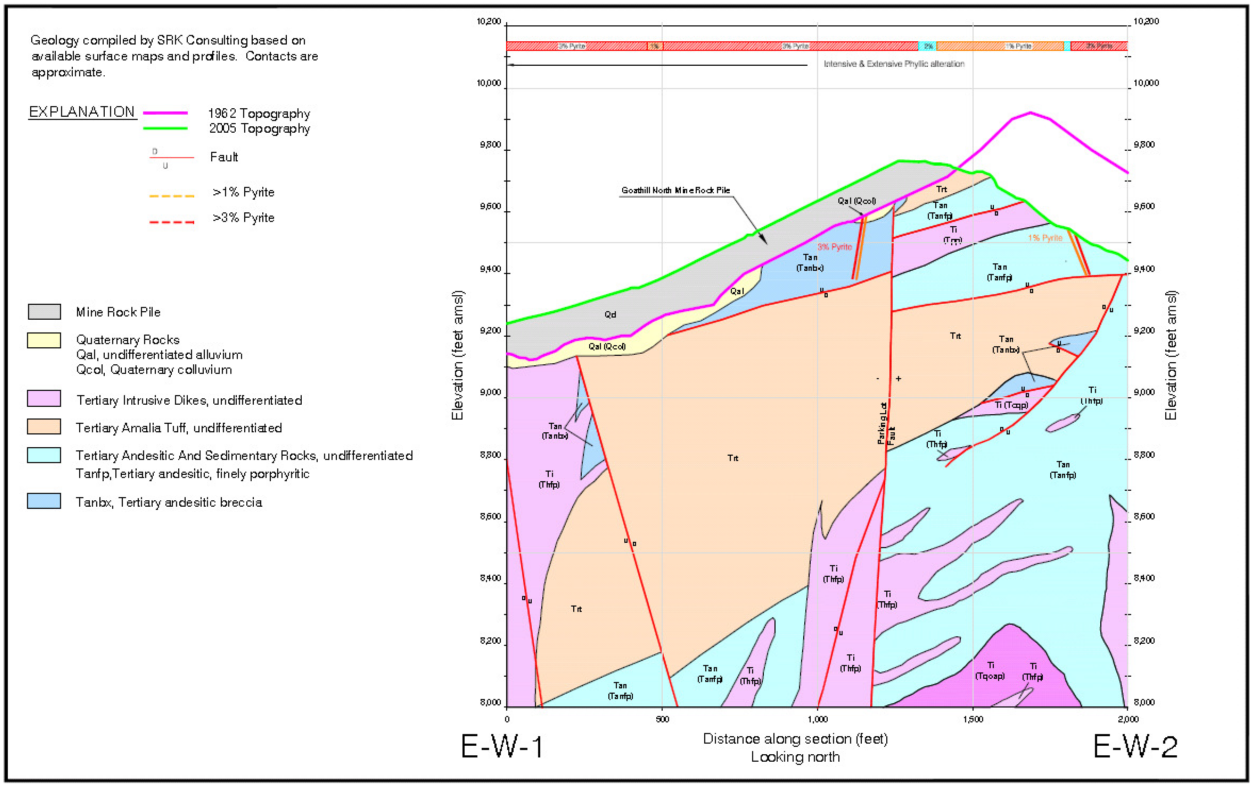

Figure 4. Goathill North Cross-Section

The geology of the Goathill North rock pile consists of a heterogeneous mixture of all the rock types discussed above. The rock pile mineralogy has been quantitatively determined using a ModAn model (Paktunc, 1998, 2001) with input parameters determined from petrographic analysis using binocular microscope, thin section analysis using a petrographic microscope, scanning electron microscope analysis, microprobe analysis, spectral analysis, X-ray diffraction, Rietveld analysis, clay mineral determination using clay separation techniques, leach tests, and evaporation tests. The results from these analyses are listed in Table 1 (McLemore, 2009b). At least 488 rock pile samples were analyzed while characterizing the rock piles. The volume of complete samples, their representativeness of the rock piles, and duplicate and triplicate analyses provides a large, high-quality data set that was used for the foundation of the water quality discussion below (McLemore, 2009a).

Table 1. Goathill North Mineral Composition

Mineral	Percentage of GHN Rock Pile	Mineral	Percentage of GHN Rock Pile
quartz	26-57	Fe oxides	0.2-7
K-spar/ orthoclase	13-27	rutile	0.2-0.6
plagioclase	0.01-29	apatite	0.01-0.8
biotite	0.01-5	pyrite	0.1-3.9
illite/sericite	5.9-26	calcite	0.2-1
chlorite	1-11	gypsum	0.2-2
epidote	0.01-7	zircon	0.03-0.06
magnetite	0.01-0.7	jarosite	0.01-2

Conceptual Hydrologic Flow

The Goathill North rock pile is located at the headwaters of Goathill Gulch, where the contributing watershed for surface water runoff and groundwater seepage is limited to the rock pile, the alteration scar escarpment to the south, and the colluvial landslide to the north. Seeps have been identified on the colluvial landslide and below the toe of the rock pile. These seeps likely predate the mining activities, due to the landslide movements that also occurred prior to mine development. Also, the seeps are on native ground adjacent to the rock pile. Prior to the rock pile regrade, water also seeped from the toe of the rock pile. Mine studies show that the potentiometric surface in the Goathill North area is at an elevation of approximately 2650 m (8700 ft), which is 150 m (500 ft) lower than the elevation of the water table at the center of the rock pile (SRK, 2007). This suggests that the seeps and elevated water levels around Goathill North are perched groundwater. This perched groundwater near Goathill North caused the design and installation of the rock drain to convey seepage water to the rock pile toe thus preventing the buildup of pore water pressures at the rock pile toe, which could impact rock pile stability. Currently, there are two seeps north of the rock pile, seepage from the rock drain, and seepage from the colluvium beneath the rock drain. The seep locations are shown on Figure 2.

The Goathill North rock pile and adjacent colluvium is instrumented with 34 vibrating wire piezometers installed in 17 boreholes. The locations are shown on Figure 2. Nested piezometers are typically installed with a sensor at the base of the rock pile, a sensor at the base of the colluvium or altered bedrock, and/or a sensor in competent bedrock. Each piezometer is connected to a data logger and a reading is taken each day. The piezometer data and seep locations were combined to develop the potentiometric surface included as Figure 2. A cross-section of the rock pile is included as Figure 5.

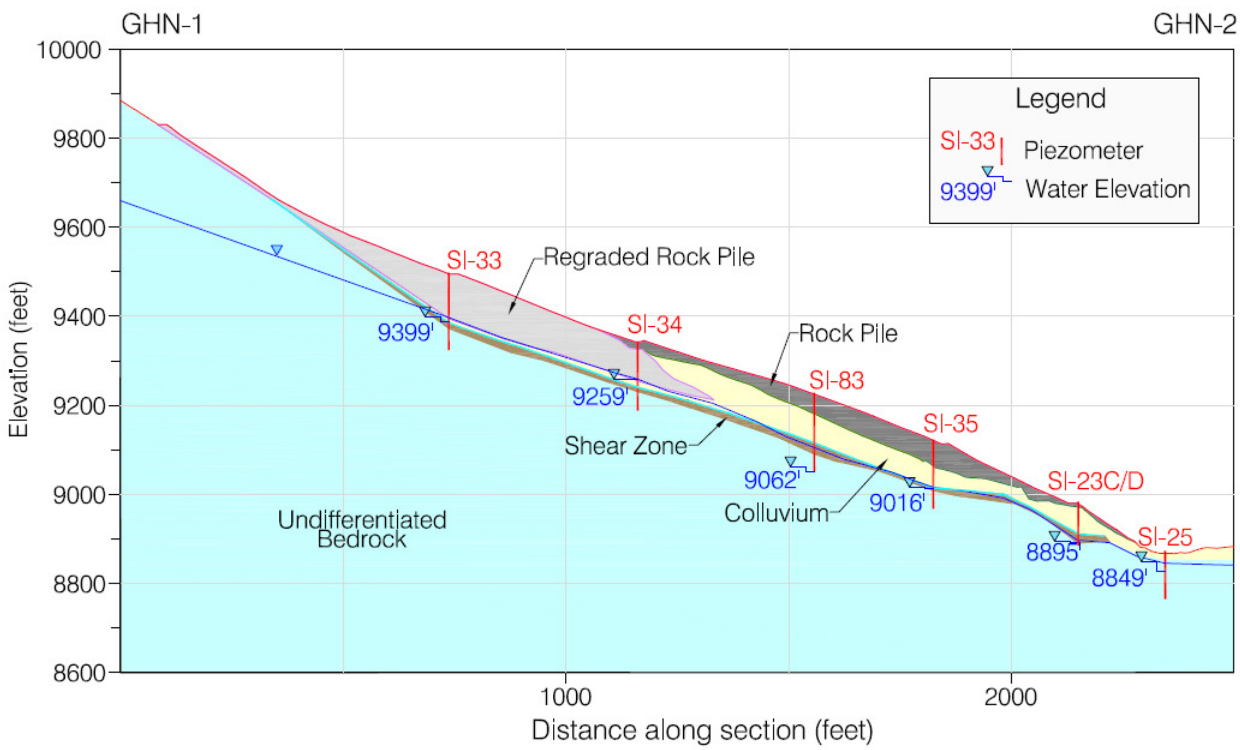

Figure 5. Goathill North Rock Pile Cross-Section

The potentiometric surface shows that groundwater flows mostly through native material, particularly the colluvium and altered bedrock, before flowing into the rock drain. Only piezometer SI-33 near the top of the rock pile indicates the water table being above the base of the rock pile by 1.2 m (4 ft). Piezometer NW-1197 (not shown in Figure 5) indicates 1.2 m (4 ft) of water in the rock drain. The rock drain was placed in the pre-regrade thalweg to a minimum thickness of 3.0 m (10 ft); therefore, the water level along the rock drain would be below the base of the rock pile. The rock drain discharges to the surface near SI-25.

Water Quality Results

Questa Mine samples the Goathill North weir seep quarterly to meet regulatory monitoring requirements, and prior to the 2010 drilling program, there were no data to represent the intermediate water quality. Boreholes SI-28D and SI-83 were drilled in 2010 to install additional geotechnical instrumentation. Water was encountered in each borehole, and samples were collected by URS personnel (URS, 2011). This water quality analysis employs four sets of water quality data, which are listed in Table 2.

Isotopic sampling performed during the Weathering Study showed that all seepage water sampled in the Goathill North vicinity was meteoric in origin (Campbell, 2008). For this analysis, rainwater is assumed to be pure water, and any dissolved material is assumed to be concentrations that are negligible when compared to the concentrations measured at the Goathill North spring.

Borehole SI-28D is adjacent to the rock pile and located within the area of the historic landslide, as shown on Figure 2. The borehole was drilled with a sonic rig, and 102 mm (4-inch) core was obtained. A weak layer of pre-sheared material was encountered between 16.8 m (55 ft) and 17.7 m (58 ft). This zone contained water, and drilling operations were suspended so a sample could be collected. Within approximately 30 minutes, the water level rose to a depth of 6.4 m (21 ft) and a water quality sample was collected. The sampler retrieved water from the borehole using a bailer. No additional water was purged from the borehole, because all water in the borehole had seeped into the borehole from the formation. The sampler noted the water to be “milky white” even after filtering the water with a 0.45 µm filter to obtain dissolved metal results. The sample included three bottles: one unfiltered and unpreserved, one filtered and preserved with sulphuric acid, and one filtered and preserved with nitric acid. Field parameters included pH, EC, temperature, DO, and ORP (URS, 2011).

Borehole SI-83 is in the middle of the rock pile and located roughly adjacent to borehole SI-28D, as shown on Figure 2. The borehole was drilled with a sonic rig, and 102 mm (4-inch) core was obtained. The rock pile material extended to a depth of 19.5 m (64 ft). Several layers of pre-sheared material were encountered in SI-83 at depths between 32.9 m (108 ft) and 41.5 (136 ft). Each weak layer was identified to contain water, but no water could be collected from the uppermost layer at 32.9 m (108 ft). The borehole was left open overnight between 41.1 m (135 ft) and 47.2 m (155 ft). In the morning, the water level in the borehole was 32.5 m (106.7 ft), and a water quality sample was collected. The sampler retrieved water from the borehole using a bailer. No additional water was purged from the borehole, because all water in the borehole had seeped into the borehole from the formation. The sampler noted the water to be “milky white” even after filtering the water with a 0.45 µm filter to obtain dissolved metal results. The sample included three bottles: one unfiltered and unpreserved, one filtered and preserved with sulphuric acid, and one filtered and preserved with nitric acid. Field parameters included pH, EC, temperature, DO, and ORP (URS, 2011).

CMI personnel have routinely sampled the Goathill North Seep at the toe of the rock pile for 9 years. Water seeping from the drain flows onto a concrete pad and then through a fiberglass weir. The sampler collects a grab sample of the surface water. Field parameters included pH, EC, temperature, DO, and ORP. The Goathill North Seep water quality data presented in Table 2 are representative of the steady-state chemistry and flow rate from the seep.

The water quality results from the 2010 drilling program show intermediate geochemistry between natural rainwater and water from the Goathill North Seep, which has contacted greater amount of minerals.

Table 2. Water Quality Sampling Results Summary

Parameter	Sample Fraction	Units	Rain Water[1]	SI-28D 55 feet	SI-83 115 feet	Goathill North Seep at Toe
Alkalinity (as $CACO_3$)	Total	mg/L	0	63	<5	<5
Bicarbonate (as $CaCO_3$)	Total	mg/L	0	63	5	NA
Carbonate (as $CaCO_3$)	Total	mg/L	0	<5	<5	NA
Hardness (as $CaCO_3$)	Dissolved	mg/L	0	2,500	2,800	NA
Hydroxide (as $CaCO_3$)	Total	mg/L	0	<5	<5	NA
Total Dissolved Solids	Total	mg/L	0	4,000	10,000	16,800
Total Suspended Solids	Total	mg/L	0	NA	4,000	NA
Aluminum	Dissolved	µg/L	0	140,000	390,000	1,200,000
Calcium	Dissolved	µg/L	0	480,000	380,000	390,000
Copper	Dissolved	µg/L	0	2,800	<40	7.8
Iron	Dissolved	µg/L	0	60,000	1,400,000	340,000
Magnesium	Dissolved	µg/L	0	220,000	440,000	670,000
Manganese	Dissolved	µg/L	0	16,000	110,000	460,000
Potassium	Dissolved	µg/L	0	<10,000	71,000	<31,000
Silicon	Dissolved	µg/L	0	31,000	24,000	NA
Sodium	Dissolved	µg/L	0	32,000	30,000	<16,000
Zinc	Dissolved	µg/L	0	4,000	20,000	84,000
Chloride	Total	mg/L	0	11	<11	26
Fluoride	Total	mg/L	0	2.5	25	120
Nitrate+Nitrite as N	Total	mg/L	0	<0.5	0	<0.2
Sulfate	Total	mg/L	0	2,500	14,000	14,000
pH	Total	SU	7	6.12	4.49	2.78
Specific Conductivity	Field	µs/cm	0	3,697	7,633	7409
Temperature	Field	°C	NA	16.41	9.18	12.14
Dissolved Oxygen	Field	mg/L	NA	5.26	1.56	15.27
Redox Potential	Field	mv	NA	264.1	94.3	490.1

[1] Assumed Values

Water Quality Discussion

The meteoric water that falls in the Goathill North vicinity infiltrates and undergoes continuous changes in geochemistry as minerals are encountered. This geochemical evolution is shown by the changes in concentrations between the samples. Rainwater falls and a percentage of that water infiltrates into the rock pile or native colluvium partially dissolving minerals. Dissolution of these minerals causes the elevated results observed in each of the three locations sampled. Coarse-grained layers within the rock pile allow for continuous advective flux of air preventing the formation of an anoxic environment.

The water quality results from SI-28D indicate contact with minerals such as fluorite, calcite, chlorite, and pyrite. The water pH (laboratory) is 6.12, while there are elevated concentrations of calcium, iron, and sulfate and some remaining alkalinity, suggesting acid rock drainage (ARD) that has been partially countered by the buffering capacity of the calcite. The presence of these minerals has been confirmed by petrographic analyses (McLemore, 2009c). Dissolved oxygen remains at 5.26 mg/l, which allows the ARD reactions to continue.

Water flowing from SI-28D towards SI-83 continues to dissolve these same minerals causing higher concentrations for most of the constituents. The concentrations for some constituents (i.e. calcium) decrease suggesting materials are being precipitated, such as gypsum. Other decreasing concentrations (e.g., silicon and sodium), probably reflect changing water-rock ratios or other reaction processes. Most metal concentrations continue to increase; however, the iron concentration has increased dramatically, suggesting continued pyrite oxidation. Also, the pH has decreased from 6.12 S.U. to 4.49 S.U. The total alkalinity concentrations are below the detection limit indicating the pH buffering capacity has been consumed. The dissolved oxygen has reduced to 1.56 mg/l, and there remains some potential for continued pyrite oxidation.

Additional reactions with pyrite cause the pH to continue to decrease from SI-83 to the Goathill North Seep. This continued reaction between the water and pyrite suggests that iron and sulfate concentrations should increase between SI-83 and the Goathill North Seep locations; however, precipitation of ferrihydrite, goethite and jarosite has significantly decreased the iron concentrations. The continued increases in the concentrations for many other constituents (i.e. aluminum and fluoride) show that the dissolution of the same minerals previously mentioned is an ongoing process, with mass increasing for parameters that do not reach solubility limits in these complex waters. The decrease in pH is likely due to continuing pyrite oxidation, but could also be contributed to by other factors, such as oxidation of ferrous iron. The sulfate concentration is the same at SI-83 and the Goathill North Seep suggesting that roughly equal amounts of sulfate are being released by pyrite oxidation as are being precipitated as gypsum. The dissolved oxygen concentration has increased, as expected, due to the sample being collected from surface water and the highly advective potential of the coarse-grained drain rock material.

Thermodynamic calculations confirm that the low-pH, high sulfate water is likely to precipitate secondary minerals such as ferric hydroxides and hydroxysulfates. Table 3 lists the saturation indexes in the Goathill North Seep water for minerals of interest (adapted from Logsdon, 2008). The data suggest that iron hydroxides and silica are supersaturated and tend to be precipitated, while calcite, clays, chlorite, and pyrite are undersaturated and will tend to be dissolved.

Table 3. Saturation Indicies for GHN Seep Water

Mineral	**S.I.**	**Mineral**	**S.I.**
Goethite	4.11	Smectites	-7.49 to -10.8
Jarosite-K	3.75	K-feldspar	-7.94
Silicagel	0.27	Calcite	-9.04
Gypsum	-0.02	Halloysite	-11.0
Am. Silica	-0.08	Illite	-18.2
Gibbsite	-3.94	K Mica	-19.0
Am. Al(OH)3	-6.78	Chlorite - 14A	-59.0
Pyrophyllite	-3.68	Chlorite - 7A	-62.5
Kaolinite	-5.79	Pyrite	-235

Rock Drain Performance

The Goathill North rock drain conveys seepage water from within and under the rock pile to the ground surface to prevent buildup of pore water pressure at the toe of the rock pile, which could negatively impact rock pile stability. The rock drain was placed along the thalweg of the gully prior to the rock pile regrade to a minimum depth and width of 3.0 m (10 ft). The drain slopes steeply while beneath the rock pile as shown in Figure 5, but the slope decreases near the drain outlet. The cover thickness also decreases to less than 3.0 m (10 ft) at the toe of the rock pile.

Approximately two years after the completion of the rock pile regrade, seepage water stopped flowing from the drain outlet and started flowing from the rock pile toe. The change in slope and cover thickness, combined with the deposition of iron oxides is the likely cause of the seep migration. The seep area was excavated, and a perforated pipe was installed to better convey the seepage water to the drain outlet. This repair worked for approximately two years before the flow from the pipe decreased and water again started flowing from the rock pile toe. This seep was also excavated and a pipe installed so that water would flow from the seep to the drain outlet. Figure 6 shows the drain rock at the seep location. The drain rock is a gray, non-reactive aplite, but contact with the water in the drain has coated each rock with iron hydroxides. On the second repair, a “P-trap” was added to the pipe inlet in an attempt to prevent oxygen from flowing up the pipe and causing iron oxides to precipitate. Figure 7 shows the recent drain repair, including the drain pipes and backfill drain rock. Again, after approximately two years, the seep migrated to the toe of the rock pile; this is the current condition. Figure 8 shows the iron-stained outlets of the drain pipes. Immediately following the pipe installation, all the water flowed from the larger pipe, and since then, an increasing amount of flow has discharged from the smaller pipe. Also, flow from pipes installed during the initial repairs (not shown) has continued to decrease while the flow from the most recent repair has increased.

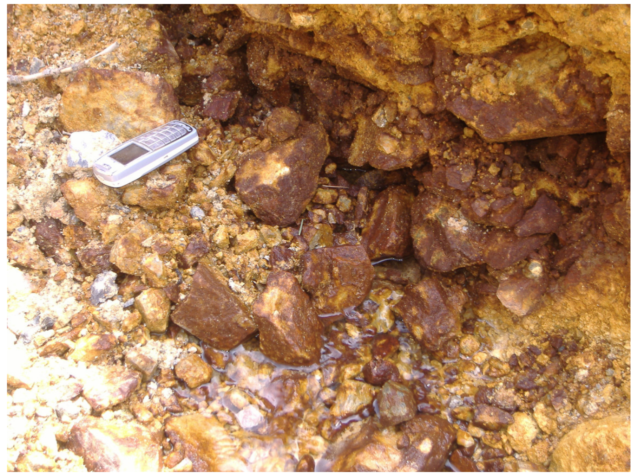

Figure 6. Iron Hydroxide on Drain Rock

Figure 7. Drain Repair

Figure 8. Pipes from Drain Repair

Piezometers NW-1197 and NW-1198 were installed during the recent repair to monitor flow levels in the rock drain. Piezometer NW-1197 is located approximately 70 m (230 ft) uphill from the rock pile toe. The piezometer is screened in the drain material. Piezometer NW-1198 is located immediately below the rock pile toe on native ground. A vibrating wire piezometer was placed at a depth of 5.52 m (18.1 ft) after excavating a seep and installing drain pipes during the recent repair. The data from piezometer NW-1197 show a relatively constant water level, indicating that iron hydroxide precipitation has not affected the performance of the upper section of the rock drain. Data from NW-1198 show an increase in water level that coincides with the seep migration, and the water level continues to rise. The hydrographs for these locations are included as Figure 9.

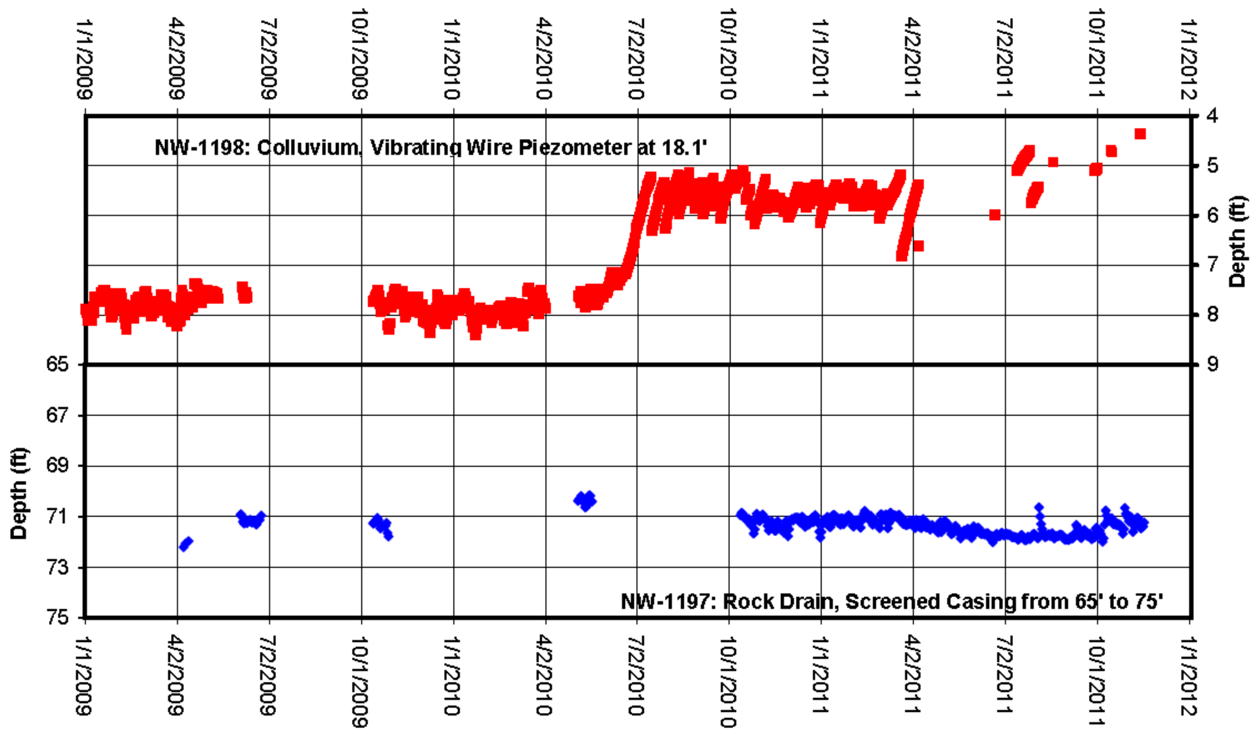

Figure 9. Hydrographs of NW-1197 and NW-1198

Conclusions

Water samples from adjacent to, beneath, and downhill from the Goathill North rock pile at Chevron Mining Inc.'s Questa Mine demonstrate the evolution of water quality from relatively pure rainwater to ARD impacted water with low pH and high metal concentrations. The groundwater in the vicinity of Goathill North is meteoric in origin, and it flows roughly parallel to the surface topography and towards a rock drain placed in the thalweg prior to the rock pile being regraded to halt a landslide that predated the mining activities. The bedrock geology is primarily an ash flow tuff with andesitic intrusions, which have been hydrothermally altered. The hydrothermal alteration deposited the molybdenum ore and minerals such as pyrite, calcite, and fluorite. The water quality samples represent conditions upgradient from the rock pile in the colluvium, conditions beneath the rock pile in the colluvium, and drain outflow conditions.

As the groundwater flows towards the drain outlet, the water quality changes due to contact with pyrite, calcite, and other minerals. The presence of these minerals has been confirmed by petrographic analyses. The pH decreases with each sample. Most metal concentrations increase with each sample. Iron concentrations decrease at the drain outlet sample due to precipitation of iron oxides in the lower part of the rock drain. Calcium also decreases and sulfate remains at steady concentrations as gypsum is deposited. Thermodynamic calculations suggest that these minerals should be being deposited or dissolved.

The geochemical instabilities near the drain outlet have caused the rock drain and subsequent repairs to clog with iron oxides, as expected due to the water pH, high metal concentrations, and advection of oxygen through the porous drain material. This clogging of the drain material has cause seep migration from the drain outlet to the rock pile toe.

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